9^{th} ASCE Joint Specialty Conference on Probabilistic Mechanics and Structural Reliability

PMC2004

July 26-28, 2004
Albuquerque, New Mexico

American Society of Civil Engineers
Sandia National Laboratories

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INTRODUCTION TO THE TECHNICAL PROGRAM

Welcome to the Ninth ASCE Joint Specialty Conference on Probabilistic Mechanics and Structural Reliability (PMC2004). Since their inception, these conferences of the ASCE have established themselves as major international scientific events, drawing scientists and engineers worldwide from government, academia and industry.

The technical program reflects the breadth, depth and vitality of the field, with 3 plenary lectures and over 200 presentations in 42 technical sessions. Increased participation by scientists from Sandia National Laboratories, our host institution, and the other U.S. National Laboratories is another striking feature of this year's technical program. The U.S. national laboratories are centers of excellence in the overall U.S. program in computational science, especially in the validation of computational models. We hope that their active participation in PMC2004 will generate new and fruitful interactions with the rest of the probabilistic mechanics and structural reliability communities.

We wish to thank the members of the Steering and Scientific Program Committees and the session organizers for developing what we believe to be an outstanding technical program. We also would like to thank the local organizing committee and especially the Conference Coordinators, Tammy Eldred and Sandy Pino, for their untiring efforts in support of the Conference.

It is our pleasure to have our colleagues from the probabilistic mechanics and structural reliability communities from around the world visiting us here in Albuquerque. We wish you an enjoyable and rewarding meeting.

Steve Wojtkiewicz
Structural Dynamics Research
Sandia National Laboratories
Conference Co-chair, PMC2004

Roger Ghanem
Civil Engineering
Johns Hopkins University
Conference Co-chair, PMC2004

John Red-Horse
Validation and Uncertainty Quantification
Sandia National Laboratories
Conference Co-chair, PMC2004

Objectives

Probabilistic mechanics and reliability analysis are valuable and powerful tools in many engineering disciplines. As variabilities and uncertainties in design parameters and behaviors are increasingly considered in the design of engineering systems, both applied and basic research in the area of stochastic mechanics will continue to grow.

For this reason, Sandia National Laboratories will host the Ninth ASCE EMD/SEI/GI/AD Joint Specialty Conference on Probabilistic Mechanics and Structural Reliability, one of the most prestigious international meetings addressing these fields. The conference will be held July 26-28, 2004, in Albuquerque, New Mexico, at the Albuquerque Sheraton Old Town Hotel located in historic Old Town.

This conference, held every four years, will bring together researchers and scientists from around the world. State-of-the-art developments in all areas of stochastic mechanics will be presented and discussed. Engineers, researchers, and scientists involved in reliability of structural, mechanical, marine, aerospace, geotechnical, and environmental systems are invited to participate.

Topics

Civil Infrastructure Systems	Codes and Standards
Computational Stochastic Mechanics	Damage and Maintenance
Earthquake Engineering	Expert Systems
Fatigue and Damage Control and Detection	Fatigue and Fracture Mechanics
Flow Induced Vibrations	Geotechnical Systems
Model Validation	Monte Carlo Simulations
Non-Linear Stochastic Differential Equations	Optimization Under Uncertainty
Pressure Vessels and Piping	Probability Methods in Design/Analysis
Random Vibrations	Safety of Aerospace Systems
Safety of Bridges and Offshore Structures	Safety of Nuclear & Geotechnical Systems
Site Characterization	Stability and Bifurcation
Statistical Analysis	Stochastic Finite Elements
Stochastic Modeling of Environmental Loads	Structural Control
Structural Damage	System Identification
System Reliability Random Processes	Random Fields
Risk Management	Uncertainty Quantification
Wave Propagation	Wind Engineering

Technical Program

Sunday, July 25, 2004

8:00am-8:00pm	Committee Meetings
2:00pm-7:00pm	Registration
6:00pm-8:30pm	Icebreaker

Monday, July 26, 2004

7:00am-4:30pm	Registration
7:00am-8:30am	Continental Breakfast
8:00am-8:30am	Welcome Session
8:30am-9:30am	Plenary Session
9:30am-10:00am	Coffee Break
10:00am-12:00pm	Concurrent Sessions
12:00pm-1:00pm	Lunch
1:00pm-3:00pm	Concurrent Sessions
3:00pm-3:30pm	Coffee Break
3:30pm-5:30pm	Concurrent Sessions
6:00pm-8:30pm	Reception

Tuesday, July 27, 2004

7:30am-4:40pm	Registration
8:00am-8:30am	Continental Breakfast
8:30am-9:30am	Plenary Session
9:30am-10:00am	Coffee Break
10:00am-12:00pm	Concurrent Sessions
12:00pm-1:00pm	Lunch
1:00pm-3:00pm	Concurrent Sessions
3:00pm-3:30pm	Coffee Break
3:30pm-5:30pm	Concurrent Sessions
6:30pm-9:00pm	Banquet

Wednesday, July 28, 2004

7:30am-10:00am	Registration
8:00am-8:30am	Continental Breakfast
8:30am-9:30am	Plenary Session
9:30am-10:00am	Coffee Break
10:00am-12:00pm	Concurrent Sessions
12:00pm	Adjournment

Special Events and Plenary Lectures

Ice Breaker Reception
Sunday, July 25, 6:00 pm – 8:30 pm
Fireplace Room, Sheraton Old Town Hotel

Registration & Cyber Cafe
Monday – Wednesday
Ballroom D, Sheraton Old Town Hotel

Conference Reception
Monday, July 26, 6:00 – 8:30 pm
Indian Cultural Center

Conference Banquet & Awards Ceremony
Tuesday, July 27, 6:30 pm – 9:00 pm
Sheraton Old Town Hotel Courtyard

Plenary Lectures

Plenary Lecture 1: Ballroom E, Monday, July 26, 8:30 – 9:30 AM
Quantifying Uncertainty in Groundwater Flow: It's Really Dark Down There
Speaker: Larry Winter, National Center for Atmospheric Research

Plenary Lecture 2: Ballroom E, Tuesday, July 27, 8:30 – 9:30 AM
Equation-Free Modeling of Complex Systems
Speaker: Yannis G. Kevrekidis, Princeton University

Plenary Lecture 3: Ballroom E, Wednesday, July 28, 8:30 – 9:30 AM
A Probability Path in Applied Science and Engineering
Speaker: Mircea Grigoriu, Cornell University

Information about the Conference

Registration Desk

The registration desk will be open starting at 2pm on Sunday, July 25, and is located in the Alvarado D Ballroom of the Albuquerque Sheraton Old Town Hotel. Registration hours are:

Sunday	2:00 pm – 7:00 pm
Monday	7:00 am – 4:30 pm
Tuesday	7:30 am – 4:30 pm
Wednesday	7:30 am – 10:00 am

Registration Fees

Regular Participant	$450
Student	$125

The participant fee includes one set of proceedings, the banquet, the reception, and all lunches and breaks. The student fee includes one set of printed proceedings, and all lunches and breaks. If students would like to attend the banquet and/or reception, tickets may be purchased separately for these events.

Explanation of the Program Format

The technical program consists of 3 plenary lectures with approximately 200 presentations in 42 technical sessions. Each day, the morning program begins with a plenary lecture followed by 7 parallel technical sessions. The afternoon program begins immediately after lunch with two sets of parallel technical sessions.

Audiovisual Services

Each meeting room is equipped with an overhead projector and a LCD projector capable of 800 x 600 resolution. Computers are NOT provided by the conference. Additional audiovisual equipment will not be provided unless the conference organizers have approved a previous request.

If you plan to use the LCD projection equipment, we recommend that you confirm the compatibility of your computer with the projector before the start of your session. To keep the meeting on schedule, any time lost debugging audiovisual problems during your presentation will be deducted from your available time. If you encounter problems, please see the conference coordinator located at the registration desk.

Author's Preparation Area

Presenting authors can test compatibility with the provided audiovisual equipment in the author's preparation area, located in the Conference Room located in back of the Business Center at the Sheraton Old Town Hotel. Each technical session is preceded by at least a 30-minute break. We recommend that authors also use this time to make a final check of their presentation equipment.

Speaker preparation rooms will be available starting 7am on Monday, July 26 for the duration of the conference. 24 minutes are allotted for each paper. You should plan on 17-20 minutes for your presentation so as to allow a few minutes for questions and comments. Your attention to the time limit will be greatly appreciated. Each of the session rooms will have overhead projectors and computer projectors.

Internet Access

Internet access is available at the Cyber Café in the Alvarado Ballroom D of the Albuquerque Sheraton Old Town Hotel where networked computers are provided for the use of conference attendees. In addition, a wireless access point is available to connect your portable computer to the Internet. Cyber Café staff is available to assist you in using this service.

Tours

A guided visit to Casa San Ysidro in the historic village of Corrales and a ride on the Sandia Peak Aerial Tramway is available on Wednesday afternoon, from 12:30 – 5:00 PM. Price per person is $41.00 and may be purchased at the registration desk during the conference.

Casa San Ysidro is named for Corrales' patron saint, San Ysidro Labrador, and was built in the second half of the nineteenth century. Recently featured on the popular television series *The Antiques Road Show*, it contains an outstanding collection of New Mexican treasures spanning three centuries and illustrates the fascinating story of the region, from the Spanish Colonial period to the present. Nestled under old cottonwoods and elms the complex includes the main house, chapel, a weaving studio, corrals, vintage wagons, courtyards and gardens. Casa San Ysidro offers a vivid picture of life in the colonial period.

Continue to the foothills of the Sandia Mountains for a ride on the Sandia Peak Aerial Tramway, the world's longest free-span cable tramway. The 2.7-mile ride to the top will take you through four of the seven life zones found in North America. Traversing these zones is equivalent to taking a trip from Mexico City to Alaska! Once atop Sandia Peak, at an elevation of 10,375 feet above sea level, you will marvel at the thousands of square miles of breathtaking scenery and panoramic views in all directions.

Balloon Rides

You may also make reservations for balloon rides between July 25 and July 28, 2004, on-line at the PMC2004 website. Albuquerque is the hot-air ballooning capital of the world. Your adventure begins at sunrise (6am) when Rainbow Ryders, Inc. picks you up in front of the Albuquerque Sheraton Old Town Hotel and takes you to the launch site where the action begins. We inflate the rainbow balloon providing you the opportunity to become involved "hands on" as crew members and help with the inflation, or sit back and observe as the gentle giant comes alive. Your flight takes you over the beautiful Rio Grande valley. You will have breath-taking views of the City, Sandia Mountains to the East, and volcanoes to the West. The flight will last approximately 1 hour. You will be returned to the conference hotel no later than 10am.

Financial Support:

National Science Foundation

Sandia National Laboratories/ASC V&V

Technical Program

Opening Remarks and Welcoming Address

Ballroom E, Monday, July 26, 8:00 – 8:30 AM

Opening Remarks

Steve Wojtkiewicz
Sandia National Laboratories
Conference Co-Chair

Welcoming Address

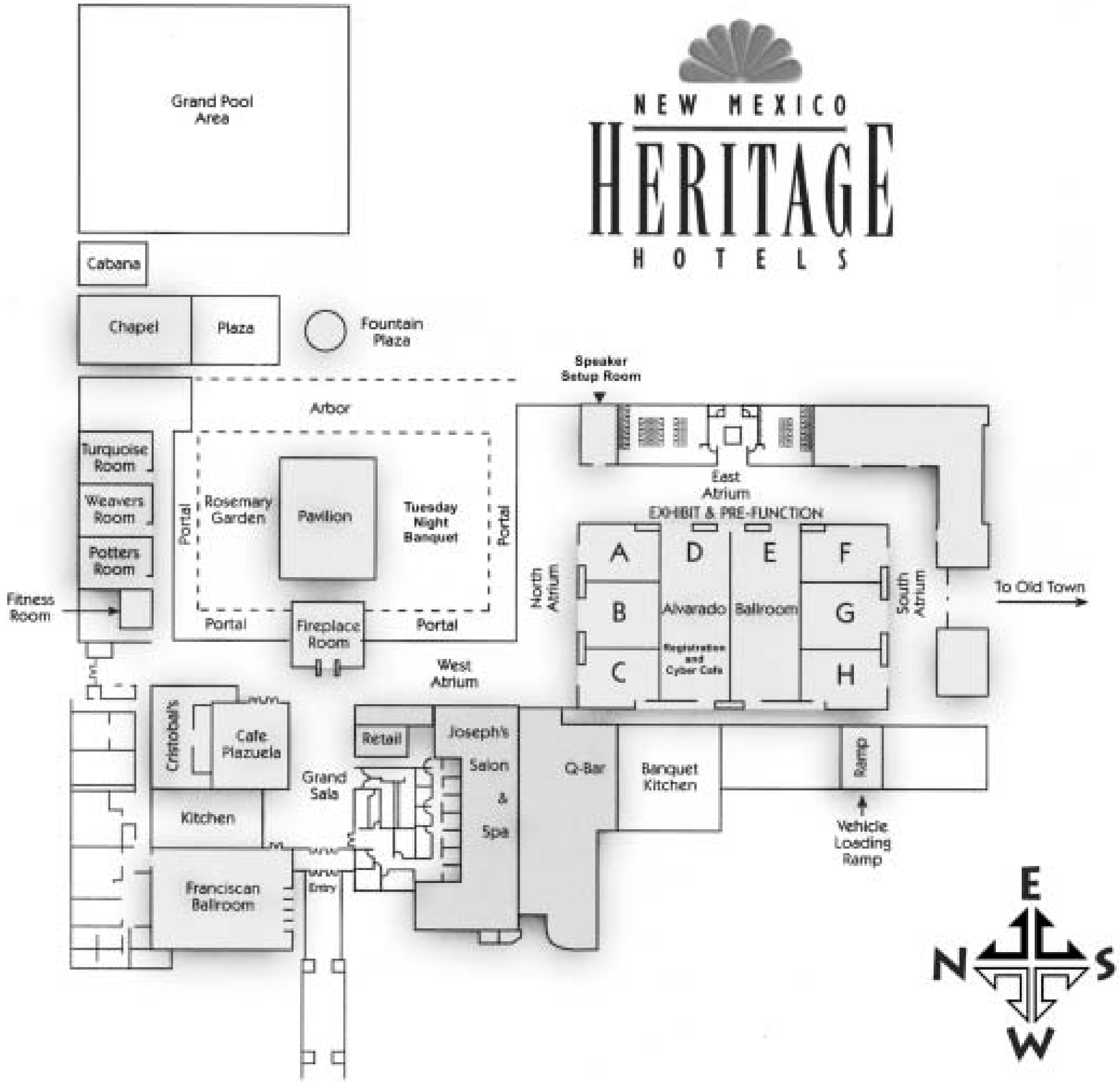
Dr. Thomas Bickel
Director, Engineering Sciences Center
Sandia National Laboratories

Plenary Lecture 1: Larry Winter

Quantifying Uncertainty in Groundwater Flow: It's Really Dark Down There

Uncertainty arises in engineering and science from many sources. My talk will deal with the effects of parametric uncertainty on our estimates of moments of system states. I will concentrate on the use of stochastic dynamics to derive state estimates, and I will motivate the talk with examples drawn from groundwater hydrology. Stochastic dynamics have a long history in groundwater because natural porous media are impossible to observe in detail. The best that can usually be done is to derive statistical estimates of system parameters from sampling and then to propagate those estimates through the underlying system mechanics. On continuum scales, flow through a porous medium is almost always described by Darcy's Equation, which relates the distribution of the system state and hydraulic pressure head to the medium's hydraulic conductivity. Details of a given conductivity field are uncertain in most cases because such fields are usually sparsely sampled, but highly variable in space. This kind of uncertainty is found in many other applications, especially those dealing with environmental health and safety. It has become common to quantify uncertainty in groundwater flow models by treating hydraulic conductivity and head as random fields. Uncertainty about conductivity is propagated through the averaged Darcy Equation to estimate statistics of head. After reviewing basic ideas of groundwater and stochastic, I will discuss the role of expert opinion in developing bounds for state variables like head.

NEW MEXICO
HERITAGE
HOTELS



Monday Technical Program: 8:00 AM – 12:00 PM

Ballroom E	**Welcome Address: 8:00 – 8:30 AM**
Ballroom E	**Plenary Session: 8:30 – 9:30 PM** Quantifying Uncertainty in Groundwater Flow: It's Really Dark Down There Larry Winter National Center for Atmospheric Research
	MONDAY MORNING, JULY 26: 10:00 AM – 12:00 PM
ROOM	**Technical Session Title**
Ballroom A	Computational Methods: Session I *
Ballroom B	Probabilistic Life-Cycle Performance Assessment, Maintenance and Management of Aging Infrastructures: Session 1 *
Ballroom C	Probabilistic Methodology and Applications in Aerospace Engineering: Session 1 *
Ballroom F	Probabilistic Representation of Input and System Properties *
Ballroom G	Uncertainty Quantification
Ballroom H	Uncertainty and Reliability in Geomechanics: Session 1 ^
Turquoise	

** Sessions Organized by ASCE Probabilistic Mechanics Committee*
^ Sessions Organized by ASCE GI RAM

Technical Program: Monday, July 26: 10:00 AM – 12:00 PM				
Time 24 Min. Talks (* Speaker)	Room: Ballroom A **Computational Methods** **Session I** Session Chairs: Bergman, L., Johnson, E.	Room: Ballroom B **Probabilistic Life-Cycle Performance Assessment, Maintenance & Management of Aging Infrastructures** **Session I** Session Chairs: Frangopol, D., Corotis, R.	Room: Ballroom C **Probabilistic Methodology and Applications in Aerospace Engineering** **Session I** Session Chairs: Zhao, Z., Wu, J.	Room: Ballroom F **Probabilistic Representation of Input and System Properties** Session Chairs: Field, R., Grigoriu, M.
10:00	A Multi-Scale Finite Element Algorithm for Solution of the Fokker-Planck Equation Masud, A., Bergman, L.*	Risk-Informed Condition Assessment of Aging Civil Infrastructure: Research Issues Ellingwood, B.*	Fatigue Damage Modeling of Composite Laminates Liu, Y.*, Mahadevan, S.	A Novel Approach for Simulation of Non-Gaussian Processes Shi, Y.*, Deodatis, G., Koutsourelakis, S.
10:24	Solution of Fokker Planck Equations Using Statistical Mixtures Wojtkiewicz, S.*	Probabilistic Maintenance Prioritization for Deteriorating Bridges Using a Multiobjective Genetic Algorithm Liu, M.*, Frangopol, D.	Advanced Probabilistic Analysis Methods for Calculating the Reliability of a Carbon-Carbon Shell for the Earth Entry Vehicle Kurth, R.*, Brust, F.	A Decision-Theoretic Approach to Model Selection for Spacecraft Re-entry Environments Field, Jr., R.*, Grigoriu, M.
10:48	FPKtool: a GUI for Solving FPK Equations for SDOF Systems Fu, T.*, Johnson, E.A., Wojtkiewicz, S.	A Multi-Level Probability-Based Assessment Procedure for Bridge Management Zandonini, R.*, Zonta, D., Bortot, F.	Stochastic Fatigue Analysis and Life Prediction for Composite Structures Zhao, Z.*, Schaff, J. R., Lin, S.	Model Selection Methods for Parametric Dynamic Models Huang, S., Mahadevan, S.*
11:12	A Neural Network Approach for Representing Realizations of Random Processes Beer, M.*, Spanos, P. D.	Reliability Analysis and Rehabilitation of Cable-Stayed Bridges with Damaged Pylons Biondini, F.*, Frangopol, D., Malerba, P.	Probabilistic Failure Prediction of Filament-Wound Glass-Fiber Reinforced Composite Tubes Under Biaxial Loading Srinivasan, S.*, Bhattacharya, B.	Treatment of Model Uncertainty in Model Calibration Swiler, L.*, Trucano, T.
11:36	A Generalized Dimension-Reduction Method for Multi-Dimensional Integration in Stochastic Mechanics Xu, H.*, Rahman, S.			Spatial Statistics Models for Stochastic Inverse Problems in Heat Conduction Wang, J.*, Zabaras, N.

Technical Program: Monday, July 26: 10:00 AM – 12:00 AM				
Time 24 Min. Talks (* Speaker)	Room: Ballroom G **Uncertainty Quanification** Session Chairs: Kareem, A., Paez, T.	Room: Ballroom H **Uncertainty and Reliability in Geomechanics** **Session I** Session Chairs: Phoon, K., Rechenmacher, A.	Room: Turquoise	
10:00	Uncertainty Quantification Using Measured Vibration Data Fonseca, J.*, Friswell, M.	Stochastic Approach to Manage the Variability from in Situ Data Cherubini, C., Vessia, G.*		
10:24	Improved Methodology for Generation of Analytical Fragility Curves for Highway Bridges Nielson, B., DesRoches, R.*	Estimating Sample Autocorrelation Functions Using Bootstrap Phoon, K.*, Fenton, G.		
10:48	Generation of Nonstationary Random Excitations with a Specified Tolerance Limit Paez, T.*, Morrison, D.	Calibration of Soil Constitutive Models with Heterogeneous Parameters Rechenmacher, A.*, Ghanem, R., Medina-Cetina, Z.		
11:12	Uncertainty Quantification of an Atmospheric Corrosion Model Sun, A.*, Moffat, H.	Assessment of Weak Stationarity Using Normalized Cone Tip Resistance Uzielli, M., Vannucchi, G., Phoon, K.*		
11:36	Modeling of Non-Stationary Winds in Gust-Fronts Wang, L.*, Kareem, A.	Characterization of Natural Variability of Hydraulic Properties of Soils Limin, Z.*, Qun, C., Zhang, L.		

A MULTI-SCALE FINITE ELEMENT ALGORITHM FOR SOLUTION OF THE FOKKER-PLANCK EQUATION

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In a recent paper, the authors developed a multi-scale finite element method for the solution of the multi-dimensional Fokker-Planck equation. The Fokker-Planck equation, and its formal adjoint the backward-Kolmogorov equation, govern the evolution of the transition probability density function of the response of a broad class of dynamical systems driven by Gaussian noise, which completely describes the system response process. Solutions employing the finite element method have heretofore been limited to dynamical systems of low dimension. The previously mentioned multi-scale method represents an effort to develop a formulation that yields significantly higher accuracies on cruder spatial discretizations, thus reducing the computational overhead associated with large scale problems occurring in higher dimensions. For example, accurate converged solutions have heretofore required meshes on the order of 100 C^0 elements per spatial dimension. In contrast, the multi-scale method reduces this requirement to 30 elements per spatial dimension with equivalent accuracy. This reduction makes tractable computations in 4 and possibly 6 dimensional phase spaces. In this paper, the multi-scale method is briefly reviewed and then applied to a model problem in order to assess computational error as a function of mesh refinement.

SOLUTION OF FOKKER PLANCK EQUATIONS USING STATISTICAL MIXTURES

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The probability density function of the response process of linear and nonlinear stochastic dynamical systems subjected to Gaussian white noise inputs is governed by Fokker-Planck-Kolmogorov equations. Closed-form solutions exist only for certain special cases. These equations have been successfully solved using finite difference and finite element methods. However, these methods have been limited to small systems (1 and 2 degrees-of- freedom).

In an effort to expand the class of systems treatable using FPK equations, a new methodology is proposed here. The probability density function is represented as a mixture of Gaussian density functions; this approximation is substituted into the appropriate Fokker-Planck equation generating an equation for the residual of the Fokker-Planck equation. This residual is then minimized at a series of evaluation points. By utilizing a statistical mixture for the approximation, the normalization, boundary, and positivity conditions imposed on the density function are automatically satisfied, oftentimes a difficulty with the under-resolved computatational grids employed by the previously mentioned numerical solution techniques. The methodology will be formulated, and its efficacy will be demonstrated through its application to several benchmark stochastic systems.

FPKTOOL: A GUI FOR SOLVING FPK EQUATIONS FOR SDOF SYSTEMS

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The responses of many linear and nonlinear stochastic dynamical systems subjected to Gaussian white noise inputs are governed by Fokker-Planck-Kolmogorov (FPK) equations. Closed-form solutions exist only for certain special cases. In 2001, the authors developed a finite-element-based MATLAB® tool [1] for solving for the transient probability density functions (PDFs) of a certain subset of single-degree-of-freedom (SDOF) dynamical systems, including linear, Duffing, and Van der Pol systems with additive and multiplicative excitation. The code focused on predefined system models with constant grid intervals. Since only a handful of systems had been studied, the full potential of the FPK tool was limited. Moreover, constant grid intervals makes it difficult to study systems that have strongly varying gradients in the system dynamic equations, resulting in significant increase of inaccuracy and computation time.

This paper describes a rewrite of this code to generalize to a larger class of system models and non-constant grid intervals. Additionally, the new code also provides a graphical user interface (GUI) for friendlier usage. The GUI can also provide an educational purpose as it gives more details of the FPK-based computation. An interactive GUI that presents the PDFs in animations helps users to understand the results from various angles. In this paper, the finite element solution approach is described, and the range of problems discussed. The responses of several example problems are presented along with the GUI.

References

[1] S.F. Wojtkiewicz, E.A. Johnson, and L.A. Bergman (2002). “FPKTOOL:A Computational Framework for the Vibration of GWN-driven SDOF Systems,” in R.B. Corotis, G.I. Schuëller, and M. Shinozuka (eds.), *Structural Safety and Reliability: ICOSSAR ’01*, CD-ROM (file FI19H02.PDF, 8 pages), Swets & Zeitlinger, Lisse, Netherlands.

A NEURAL NETWORK APPROACH FOR REPRESENTING REALIZATIONS OF RANDOM PROCESSES

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In this paper, neural networks are applied to represent stochastic processes. A first estimation for single realizations of random processes is gained from rare data. This application may be understood as a pre-stage to Monte Carlo simulation. In contrast to established probabilistic methods, neural network approaches do not require knowledge or assumptions of probability distribution functions or spectral densities. A neural network works model-free, learns directly from the data observed, and generates predictions based on the perception only.

The approach described in the paper has been developed starting from basic properties of neural networks. Neural networks have been successfully applied for solving problems that are difficult to handle based on deterministic or stochastic methods for decades. The main feature of neural networks lies in pattern recognition. Hereby, the patterns to be analyzed do not only concern images or acoustic patterns, but also "stochastic" patterns.[1]. Thus, it is reasonable to feed stochastic data to a neural network and infer to future "behavior" of the stochastic process from which the data fed originate. This approach may be particularly promising when the data available are characterized by small sample size, limited physical information, and properties that cannot be identified clearly. Preliminary successful applications support this proposition. For example, a neural network approach for forecasting wind velocities is described in [3] and compared to established probabilistic methods.

In the present study, the results from [3] regarding the kind, architecture, and training of the network have been taken into account. Based on [2], a standard feed-forward network has been constituted as multi-layer perceptron with logistic sigmoid activation functions. An appropriate architecture of the network has been found iteratively. For training the net, i.e., for adjusting all weights and biases assigned to the neurons and neural connections, a backpropagation algorithm operating with generalized delta rule has been applied. The input information for the network consists of the observations of the process at the previous r successive points in time tn-r, ..., tn-1. Output information is the predicted value of the process at the present time tn. On this basis, the net is trained with randomly selected sequences from the data observed. Then, the prediction is started with the last observed sequence as input vector and proceeded step by step in time. The capability of the neural network approach to represent stochastic behavior of a process is demonstrated by way of an example.

References

[1] Ch. M. Bishop, "Neural Networks for Pattern Recognition", Clarendon Press, Oxford, 1995.
[2] S. Haykin, "Neural Networks: a comprehensive foundation", Prentice Hall, Upper Saddle River, NJ, 1999.
[3] A. More and M.C. Deo, "Forecasting wind with neural networks", *Marine Structures*, v. 16, pp. 35–49, 2003.

A GENERALIZED DIMENSION-REDUCTION METHOD FOR MULTI-DIMENSIONAL INTEGRATION IN STOCHASTIC MECHANICS

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A new, generalized, multivariate dimension-reduction method is presented for calculating statistical moments of the response of mechanical systems subject to uncertainties in loads, material properties, and geometry. The method involves an additive decomposition of an N-dimensional response function into at most S-dimensional functions, where S ● ● N; an approximation of response moments by moments of conditional random variables; and a moment-based quadrature rule for numerical integration. A new theorem is presented, which provides a convenient means to represent the Taylor series up to a specific dimension without involving any partial derivatives. A complete proof of the theorem is given using two lemmas, also proved in this paper. The proposed method requires neither the calculation of partial derivatives of response, as in commonly-used Taylor expansion/perturbation methods, nor the inversion of random matrices, as in the Neumann expansion method. Eight numerical examples involving elementary mathematical functions and solid-mechanics problems illustrate the proposed method. Results indicate that the multivariate dimension-reduction method generates convergent solutions and provides more accurate estimates of statistical moments or multidimensional integration than existing methods, such as first- and second order Taylor expansion methods, statistically equivalent solutions, quasi-Monte Carlo simulation, and the fully symmetric interpolatory rule. While the accuracy of the dimension reduction method is comparable to that of the fourth-order Neumann expansion method, a comparison of CPU time suggests that the former is computationally far more efficient than the latter.

RISK-INFORMED CONDITION ASSESSMENT OF AGING CIVIL INFRASTRUCTURE: RESEARCH ISSUES

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The Nation's infrastructure is at risk from structural aging, leading to structural deterioration of bridges, buildings, and other facilities from aggressive chemical attack, corrosion, and other physical mechanisms. Current condition assessments of structures often are highly subjective in nature and may provide little quantitative information on margins of safety or future performance in service. Clearly, decisions regarding conditions for continued service or requirements for rehabilitation should be supported by quantitative evidence that aging or other factors has not caused strength to deteriorate to the point where the capacity of the system to withstand or mitigate future extreme events is impaired. Furthermore, rehabilitation investments should be aimed at maximizing the likelihood of successful future performance at minimum costs. Current codes of practice provide little guidance for the proper evaluation of existing facilities for continued service, since their focus is on new construction. Probabilistic risk analysis methods can provide quantitative tools for the management of uncertainty in condition assessment and are an essential ingredient of risk-informed management decisions.

Despite the research advances of the past decade, significant challenges to practical implementation of reliability-based condition assessment remain:

- Physical/chemical models of structural deterioration to supplement or ultimately supplant the current phenomenological models found in most time-dependent reliability studies;
- Appropriate performance limits for civil infrastructure;
- Computationally efficient methods for determining the limit state probabilities of structural components or systems as functions (or intervals) of time from stochastic process models of deterioration, residual strength and service and environmental loads;
- Models of in-service inspection and maintenance that account for uncertainties in the detection and measurement of aging defects and in benefits from repair, which are dependent on the specific nondestructive evaluation and repair methods selected;
- Evaluation of costs, especially tradeoffs between investment, method and extent of inspection, and required level of performance with reliability-based optimization methods;
- Probability-based benchmarks and performance metrics for stakeholder groups and decision-makers.

The paper discusses each of these research issues in turn, aiming to demonstrate the context and importance of each in infrastructure condition assessment strategies determined within a structural reliability framework.

PROBABILISTIC MAINTENANCE PRIORITIZATION FOR DETERIORATING BRIDGES USING A MULTIOBJECTIVE GENETIC ALGORITHM

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Bridge managers are facing ever-increasing tasks of prioritizing limited budgets to cost-effectively maintain normal functionality of a huge inventory of highway bridge infrastructure that shows varied deterioration severities over the intended service life. A satisfactory maintenance planning scenario should meet bridge managers' specified requirements for the optimum balance between whole-life costing and bridge performance. Due to uncertainties associated with bridge deterioration processes and with effects of different maintenance interventions, prediction of time-varying bridge performance under no maintenance and under maintenance can only be made probabilistically. Life-cycle maintenance cost should also be treated likewise.

Recently, the authors have presented a computational framework for bridge maintenance planning. A multiobjective optimization formulation was used as a powerful approach to determining a desirable maintenance solution with simultaneous consideration of bridge performance and life-cycle cost [1]. A computational model for calculating time-dependent performance profiles under no maintenance and under maintenance proposed by Frangopol et al. [2] was adopted to predict both condition and safety indices of deteriorating concrete bridge crossheads. Design variables used in the optimization were application times of maintenance interventions. In a practical situation such as maintenance bidding, bridge managers are usually expected to provide a list of prioritized annual maintenance interventions that will be applied during the remaining service life [3].

This paper presents an automatic procedure to prioritize maintenance efforts for deteriorating bridges over a designated time horizon. Within each year, any of five different maintenance strategies could be applied independently at a time instant that follows uniform distribution. Effects of uncertainties are considered by means of Monte Carlo simulation. The resulting optimization problem is solved by a multiobjective genetic algorithm. It produces a group of different sequences of annually applied maintenance interventions that leads to optimized tradeoff among condition, safety, and life-cycle maintenance cost objectives. This enables bridge managers to compare different maintenance planning alternatives and then choose a final solution that cost-effectively balances competing objectives.

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PROBABILISTIC LIFE-CYCLE PERFORMANCE ASSESSMENT, MAINTENANCE AND MANAGEMENT OF AGING INFRASTRUCTURES: SESSION 1

A MULTI-LEVEL PROBABILITY-BASED ASSESSMENT PROCEDURE FOR BRIDGE MANAGEMENT

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Assessment is an essential part of any Bridge Management System (BMS): although the main purpose of assessment is to determine the safe load carrying capacity of a bridge, accurate knowledge of the reliability index also plays a fundamental role in the decision-making process that controls retrofit, repair and reconstruction. This paper presents the safety assessment procedure that has been implemented in the BMS of the Autonomous Province of Trento (PAT). The procedure acknowledges the general guidelines resulting from the EU-funded BRIME research project [1], and consists of a 5-step process, in which the bridge is evaluated starting with simple conservative methods and progressing to more refined methods when a higher assessed load capacity is required. Levels of assessment differ in (i) the information on material properties and load models, (ii) the calculation models and (iii) the assessment method. In detail, information on material properties and load models is provided by design specifications and standards at the lower levels; and by in-situ testing and observation at higher levels. As to the calculation model, simple load distribution and elastic analysis are allowed at level 1 while more refined models should be adopted starting at level 2 that can take into account inelastic re-distribution of stresses and spatial effects in a more realistic manner. Levels 1 to 4 are LRFD-based, and aim at calculating, for each relevant limit state, the live load rating factor θ, defined as the coefficient that assesses a specific limit-state equation, of the type:

$$R_d = \gamma_G \cdot G_k + \theta \cdot \gamma_{Q1} \cdot Q_{1k} + \sum_{i=2}^{n} \theta \cdot \gamma_{Qi} \cdot \psi_{0i} \cdot Q_{ik}$$

Level 5 requires the evaluator to employ II or III order probability methods, and to report the assessment results in terms of reliability indices β [2, 3]. Factors θ and reliability indices β, obtained from the evaluation, provide information for the BMS database, and offer the manager quantitative tools for decision-making. More specifically, each allowable action is ranked with a prioritization index, which represents the rate between the expected reduction in probability of failure, and the associated additional whole-life cost. The practical application of this principle requires statistical correlation between the factors θ assessed at each level and the corresponding reliability index: this in practice is obtained by a calibration process, which includes the full application of the 5-step evaluation procedure to a number of specific case studies. In the paper, the outcome of this calibration is discussed in detail.

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RELIABILITY ANALYSIS AND REHABILITATION OF CABLE-STAYED BRIDGES WITH DAMAGED PYLONS

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In recent years, a growing number of concrete cable-stayed bridges exhibit extensive damage due to the interaction with the environment. In fact, the damaging process induced by the diffusive attack of environmental aggressive agents, like sulfate and chloride, usually leads to deterioration of concrete and corrosion of reinforcement. Such process involves several factors, including temperature and humidity, and its dynamics is governed by coupled diffusion process of heat, moisture and various chemical agents. In addition, damage induced by mechanical loading interacts with the environmental factors and accelerate the deterioration process. In cable-stayed bridges, damage tends to develop in both the deck and the pylons.

However, the effects of the deterioration of the pylons are usually more important since the percentage of damaged material volume in such elements is greater than in the deck. Clearly, this aspect is emphasized in bridges with very slender pylons.

The paper focuses on a cable-stayed bridge built in Milan (Italy). The total length of the bridge is 180 m, with a central span of 90 m and two lateral spans of 45 m. The suspension system is fan-shaped and consists of 6 stays for each pylon. The height of the two pylons with respect to the deck level is about 20 m. The pylons show very extensive damage. For this reason, the structure needs to be rehabilitated in order to assure the required structural performance. To this aim, the time-variant reliability of the bridge with respect to proper indicators of the structural performance is evaluated by means of a probabilistic analysis for both the damaged and the restored structure. Such analyses exploit the potentialities of a new procedure recently proposed by the authors for the durability analysis and lifetime assessment of concrete structures subjected to the diffusive attack from external aggressive agents. The diffusion process is modeled by using cellular automata and the mechanical damage coupled to diffusion is then evaluated by introducing proper material degradation laws. The randomness in the main parameters of the structural problem (material properties, geometry of the concrete cross-sections, area and location of the reinforcement, etc.) is accounted for by Monte Carlo simulation. Based on the results of the reliability analyses, a proper structural rehabilitation is finally planned and the effects of the selected interventions on the structural performance, as well as on the increase of the structural lifetime, are discussed.

FATIGUE DAMAGE MODELING OF COMPOSITE LAMINATES

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Composite materials are widely used in automotive, naval, and aerospace structures, where they are often subjected to cyclic fatigue loading. Fatigue is one of the most common failure modes in all structural materials, including composite materials. Due to the anisotropic properties of composite materials, the fatigue problem is multiaxial. Accurate fatigue life prediction needs to include the random variations in material properties (Young's modulus, strength, etc.), loading history, component geometry, and environmental conditions. Currently available macro-level models based on S-N curves and residual strength require extensive experimental data, and the micro-level progressive damage model is computationally difficult and time consuming [1].

This paper proposes a new damage accumulation model for fatigue life prediction of composite laminates, which reduces both computational and experimental cost. The model is constructed on the ply level and uses a new multiaxial damage index to consider the damage caused by different stress components. The fatigue life is predicted based on the proposed model and experimental results of unidirectional laminates. The numerical results are compared with experimental results for balanced laminates [2]. The predicted fatigue lives agree with the experimental observations very well. The validated model is then used for probabilistic fatigue life prediction and reliability computation.

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ADVANCED PROBABILISTIC ANALYSIS METHODS FOR CALCULATING THE RELIABILITY OF A CARBON-CARBON SHELL FOR THE EARTH ENTRY VEHICLE

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The Earth Entry Vehicle (EEV) is a proposed program to travel to Mars, collect soil samples, and return to the earth with these samples. The structure is a carbon-carbon composite wing which will re-enter the earth without a parachute system. The structure must be able to withstand several thousand degree temperature changes, large vibration loads during launch, dynamic loadings, and a 130g impact loading. Because the Mars soil must be treated as a biohazard it is necessary to demonstrate a structural failure probability, defined as the release of a 2 micron particle, of less than 1 in 1,000,000. Because of a paucity of data, incomplete engineering design, and large uncertainties in both landing sites, there are many variables needed to be treated as random. Additionally, because of composite material being modeled, advance mechanics models, that require substantial computational time, must be employed. This implies that the use of standard Monte Carlo methods is not feasible because it is necessary to define such low probabilities of failure with a high degree of confidence. This study employed advanced probabilistic methodologies to develop the estimate of the carbon-carbon failure probabilities. Response surfaces, fast probability integration using transformed random variables, discrete probability distributions, and importance sampling were all employed to calculate the structural failure probability. In addition, bootstrap techniques were applied to calculate the uncertainty in this estimate.

The results of the Phase I study indicated that the structural failure probability was slightly higher that 1 in 1,000,000. However, this estimate was based on very conservative estimates of the damage zone size and type. Delaminations, fiber and matrix cracking were all modeled. The damage sizes necessary to reduce the structural failure probabilities below 1 in 1,000,000 were identified. These limits can then be used to specify the inspection methods needed during manufacturing to insure that the structural failure will be below the design limit.

PROBABILISTIC METHODOLOGY AND APPLICATIONS IN AEROSPACE ENGINEERING: SESSION 1

STOCHASTIC FATIGUE ANALYSIS AND LIFE PREDICTION FOR COMPOSITE STRUCTURES

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The development of an accurate and reliable life prediction methodology is a vital step in the design of safe and affordable aerospace structures. This is particularly important to composite structures due to their complex failure mechanisms and inherent randomness from various uncertainty sources, including material property, initial flaw, structural and geometric configuration, operational and environment loading, and manufacturing quality. Delamination is perhaps the most critical damage mode in composite structures, and is the focus of this study.

In this paper, a systematic framework of uncertainty quantification and assessment for fatigue life of a tapered composite beam with multiple terminated plies is presented. The reliability based life prediction model for composite delamination of ply endings on tapered beams representative of helicopter tail and main rotor flexbeams is developed first. . The flexbeam is subjected to edgewise bending, flapwise bending, torsion, and centrifugal loads, and is primarily composed of unidirectional graphite and glass/epoxy. Attributes to the probabilistic analysis including material properties and geometric configurations were identified and corresponding uncertainty models were developed. Variability of as-manufactured ply ending geometry of representative flexbeams was quantified from photomicrograph inspection. Measured lamina properties and resulting uncertainty models of laminate properties were developed by integrating classical laminate plate theory with probabilistic methodology. The statistical characteristics of transverse shear stress due to presence of ply ending was estimated using elasticity ply ending stress analysis code coupled with probabilistic analysis tool. Probabilistic distributions of interlaminar shear stress and fatigue life were calculated through structural reliability analysis, for both single and double ply ending geometries. Sensitivity analysis was also employed to determine the most dominant design parameters, which governs the reliability and durability of delamination of flexbeams. It is found that the geometric uncertainties possess the most significant impact on the fatigue life over other design variables. It is also observed that the fatigue life of single ply end is several magnitudes higher than the one of double ply end. The observation clearly highlights the importance to employ advanced probabilistic analysis in fatigue life assessment of composite structures. Finally, based on testing results, an S-N type relationship is developed to predict fatigue life of ply end due to delamination. The fatigue model is also integrated with advanced probabilistic analysis capability.

As continuing effort, recent development has been devoted to a fully coupled probabilistic finite element tool and verification on a similar class of problems. Verification analysis will be conducted through comparison of results with tapered beam fatigue testing conducted under axial tension and transverse bending loading. This analysis is particularly useful in quantifying variations in manufacturing of composite tapered structures and the influence of these variations on component durability. Ultimately, probabilistic analysis and sensitivity assessment will be used to optimized manufacture tolerance of composite laminates for a given target risk level. The probabilistic analysis framework and numerical procedure being developed will be extremely useful for reliability-based design and risk-based maintenance of composite structures.

PROBABILISTIC FAILURE PREDICTION OF FILAMENT-WOUND GLASS-FIBER REINFORCED COMPOSITE TUBES UNDER BIAXIAL LOADING

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Filament-wound, fiber-reinforced polymer-matrix composite laminate tubing has been used for a wide range of engineering applications, owing to their high specific stiffness, strength and superior corrosion resistance. Leakage failure in the composite tubing under multiaxial loading has been an important subject of concern but not well understood. Extensive analytical and experimental investigations have recently been reported [1, 2] on leakage failure predictions for composite tubes. These investigations developed deterministic estimates of leakage failure of composite tubes under different combinations of axial load and internal pressure. Effects of uncertainties in material properties and laminate construction on leakage failure need to be studied in detail. In this study, probabilistic analyses are performed to predict leakage failure of angle ply composite laminate tubes under combined internal pressure and axial loading. Three design random variables with uncertainties are selected: (1) elastic moduli along principal lamina directions; (2) uniaxial matrix-dominated strengths of each lamina; and (3) spatial variation of thickness of individual plies. The probabilistic analysis is performed by stochastic finite element analysis using the ANSYS program and the Monte-Carlo Method. Influence of each design random variable on leakage failure is evaluated. These are compared with experimental results available in the literature [1, 2].

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A NOVEL APPROACH FOR SIMULATION OF NON-GAUSSIAN PROCESSES

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A class of spectral-representation-based approaches for simulation of non-Gaussian processes is using iterative schemes that upgrade the spectral density function of an underlying Gaussian process according to the theory of translation processes. This iterative upgrading is performed until both the spectral density function and probability distribution function of the simulated non-Gaussian process match the corresponding targets within a prescribed level of tolerance. A side effect of this iterative scheme is that the underlying “Gaussian process” becomes gradually non-Gaussian. It is therefore necessary to compute the empirical cumulative distribution function of the underlying “Gaussian process” at every iteration step in order to properly map it to the prescribed non-Gaussian distribution. Consequently, the simulated non-Gaussian process is not a translation process anymore, as it is not obtained by mapping a Gaussian process to a non-Gaussian one. In this work, a novel iterative scheme based on a Markov Chain Monte Carlo algorithm is proposed so that the underlying Gaussian process remains Gaussian and the translation process concept is preserved throughout the entire iterative process. Various characteristics of the proposed simulation approach are examined including its computational efficiency and ability to deal with highly skewed non-Gaussian processes. Examples are provided for both scalar and vector processes.

A DECISION-THEORETIC APPROACH TO MODEL SELECTION FOR SPACECRAFT RE-ENTRY ENVIRONMENTS

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A decision-theoretic approach is developed for selecting the optimal member from a collection of competing models. The approach can be applied to collections of probabilistic or deterministic models. Each model in the collection is consistent with available data and any knowledge of the system being modeled. A performance criterion is used to select the optimal model within the collection, based on postulated utility functions. It is shown that utility functions can be selected such that the decision-theoretic framework favors a conservative model, even if data is limited.

The methodology is applied to select optimal pressure field models for loads encountered during the atmospheric re-entry of a spacecraft. The competing models form a class of Gaussian and non-Gaussian, stationary stochastic processes with prescribed second-moment properties in both space and time. The response of a critical internal component is used as the performance criterion.

MODEL SELECTION METHODS FOR PARAMETRIC DYNAMIC MODELS

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Mechanical joints are largely responsible for the energy dissipation and vibration damping in weapons systems. Modeling the energy dissipation mechanism of such joints is usually quite complicated, and empirical parametric models are deduced by mechanical testing procedures. Model selection is an important part of parametric model calibration based on test data for dynamic computational models. In particular, when the test data is limited, model selection helps make a right trade off between overfitting and underfitting.

A number of quantitative and statistical techniques have been and are being developed for model selection. Choosing the most suitable technique is made difficult by many competing approaches, including cross validation, the Akaike Information Criterion (AIC), the Bayesian approach (e.g. Bayesian Information Criterion), Discriminative Information Criterion (DIC), Minimum Description Length methods and so on. The relationship among these model selection methods and their relative merits need to be investigated. Various model selection methods are studied and compared in this paper and illustrated in the context of model selection for the characterization of dynamic behavior of lap-joints where a couple of parametric models are available.

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TREATMENT OF MODEL UNCERTAINTY IN MODEL CALIBRATION

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The problem of model calibration is often formulated as finding the parameters that minimize the squared difference between the model-computed data (the predicted data) and the actual experimental data. This approach does not allow for explicit treatment of uncertainty or error in the model itself: the model is considered the "true" deterministic representation of reality. While this approach does have utility, it is far from an accurate mathematical treatment of the true model calibration problem in which both the computed data and experimental data have error bars. Our proposed research focuses on methods to perform calibration accounting for the error in both the computer model and the data, as well as improving our understanding of its meaning for model predictability. We call this approach Calibration under Uncertainty (CUU).

This talk presents our current thinking on CUU. We outline some current approaches in the literature, and discuss the Bayesian approach to CUU in detail. Recent research in the Bayesian statistics community has yielded advances in formal statistical methods that address CUU. One approach is that of Kennedy and O'Hagan (2001). They formulate a model for calibration data that includes an experimental error term (similar to standard regression) and a model discrepancy term, with a Gaussian process chosen to model the discrepancy. They then use a Bayesian approach to update the statistical parameters associated with the discrepancy term and with the model parameters. We discuss several issues relating to the Bayesian approach: First, is the Gaussian prior the correct one, or the most effective choice for complex CSE models? The current emphasis on Gaussian priors has a rich basis in spatial statistics and inference from random fields. However, there are alternative priors and we need to clearly understand the strengths and weaknesses of various choices. Second, the mathematics behind this approach involves covariance matrices of joint input variable distributions. Estimating the full joint posterior distribution involves complicated integration and so techniques like Markov Chain Monte Carlo (MCMC) sampling are used to approximate the posterior distributions on the hyperparameters which govern the prior distribution. We discuss MCMC methods and their suitability to the CUU problem. Finally, the approach of Kenney and O'Hagan assumes that the computer simulation model is deterministic: re-running the model with the same set of inputs produces the same output. We propose extending their framework to allow for stochastic simulation models.

This talk will address the definition of "optimal" parameter setting, in the context of both maximizing agreement between the model's computed results and experimental data AND incorporating the uncertainty inherent in the model into the computed results. "Optimal" also involves determining the parameter settings that may be used for as many extrapolations as possible: settings that are valid outside the range of the experimental data in many situations, making model extrapolation a viable and valid task. This problem strikes at the heart of a current question of great importance: What is the proper relationship of calibration to validation? Directly quantifying model uncertainty in the mathematics of calibration increases our understanding of the anticipated predictability of the model, one of the key goals of validation.

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PROBABILISTIC REPRESENTATION OF INPUT AND SYSTEM PROPERTIES

SPATIAL STATISTICS MODELS FOR STOCHASTIC INVERSE PROBLEMS IN HEAT CONDUCTION

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Uncertainties such as measurement noise are unavoidable in inverse problems, and often lead to unfavorable solutions due to the ill-posed nature of the problem. Although the uncertainties are stochastic in nature, there are rich statistical information contained in the actual data. A Bayesian statistical inference approach is presented here for the solution of stochastic inverse problems in heat conduction. Spatial statistics models, in particular Markov Random Fields (MRF), are used to model the prior correlations of unknown thermal quantities (boundary heat flux or heat sources) at different sites and time points. The joint posterior probability density function (PPDF) of unknown heat quantities is derived and then exploited using Markov Chain Monte Carlo (MCMC) algorithm, in particular Gibbs sampler. Both Maximum A Posteriori (MAP) and posterior mean estimates and associated statistics are computed using MCMC samples, and compared with the Maximum Likelihood Estimate (MLE). An augmented Bayesian formulation is also presented to estimate the statistics of measurement noise simultaneously with the unknown heat quantities. The intrinsic relations between Tikhonov regularization, spatial statistics models and Expectation-Maximization algorithm (EM) are revealed. Typical examples of reconstructing boundary heat flux and heat sources from thermocouple readings are presented to demonstrate features of the proposed methodologies.

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UNCERTAINTY QUANTIFICATION USING MEASURED VIBRATION DATA

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A typical uncertain vibration analysis is the determination of the natural frequencies statistics given the statistics of uncertain parameters (such as material properties or geometric dimensions). This is referred as the *forward uncertainty propagation* problem and well established methods are available to solve it, such as the Monte Carlo method and the perturbation method.

The knowledge of the uncertain parameters distribution is a precondition to apply any of the methods referred above. In some cases it may be possible to directly measure samples of the uncertain parameters but quite often is easier to measure the output quantities (e.g., is easier to measure global natural frequencies or FRF's than localized material properties such as densities or thicknesses). The uncertain parameters statistics could then be inferred and modeled from those measurements, and that knowledge could be applied to new problems. This is the interest of *uncertainty identification,* here seen as the reserve problem of estimating the uncertain parameters distribution from measured vibration data.

A robust and efficient method for the uncertainty quantification will be presented. It results from applying the maximum likelihood estimation of the uncertain parameters distribution to the existing forward uncertainty propagation methods. A cantilever beam with a point mass at an uncertain position will be used as application.

UNCERTAINTY QUANTIFICATION

IMPROVED METHODOLOGY FOR GENERATION OF ANALYTICAL FRAGILITY CURVES FOR HIGHWAY BRIDGES

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Seismic risk assessment methodologies require seismic bridge fragility curves as input. For these methodologies to be effective there is a need for reliable fragility curves. Therefore it is necessary to evaluate ways to improve the methodologies for generating analytical bridge fragility curves. When using analytical methods to generate bridge fragility curves, it is important that all major seismically vulnerable bridge components be considered.

In this paper two bridges are analyzed which consider three major vulnerable bridge components, namely the columns, fixed bearings and expansion bearings. A methodology to combine the fragility curves for these individual components into a system fragility curve is presented. This methodology is then applied to two bridge classes that are typical to the Central and Southeastern United States. The results from these two bridges show that there can be significant error in the estimation of the bridge fragility curve when the assumption that the column fragility is representative of the entire system is used. In some damage states errors could be as large as 100 percent. This supports the recommendation that all major vulnerable components (e.g. columns, fixed bearings, expansion bearings, abutments and foundations) need to be considered when generating bridge fragility curves.

GENERATION OF NONSTATIONARY RANDOM EXCITATIONS WITH A SPECIFIED TOLERANCE LIMIT

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Most practical structural dynamic phenomena involve excitations and responses that are random processes. In the traditional, stationary case these random processes are modeled using Fourier-based analyses. But in the most practical and frequently encountered case of nonstationary random processes, the most accurate and efficient model is the Karhunen-Loeve (KL) expansion. This model is based on the eigenvalue expansion of the autocovariance function of the random process, and represents the random process as an expansion involving principal shapes, corresponding amplitudes and a sequence of uncorrelated, zero-mean, unit-variance random variables. The KL expansion for a nonstationary random process can be obtained using experimentally measured random process realizations, but if it is, there is, of course, some level of statistical error associated with the identified parameters of the model. This statistical error occurs because of the finiteness of the data set used in the identification process. This paper demonstrates a technique for statistical analysis of the KL model. It shows how the Bootstrap can be used to generate nonstationary random process realizations that satisfy a specified tolerance limit. Experimental data are used to demonstrate use of the model.

UNCERTAINTY QUANTIFICATION

UNCERTAINTY QUANTIFICATION OF AN ATMOSPHERIC CORROSION MODEL

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Atmospheric corrosion of electrical components occurs in a stochastic fashion which is difficult to model using deterministic reaction kinetics. We currently have a kinetics model to describe the copper sulfidation corrosion process in Sandia's aging engineering components. Concurrent to the model development, uncertainty analysis is carried out to ascertain the variability of model response given the uncertainties in the input parameters. This study will detail the work of interfacing the growth model to an uncertainty quantification solver, namely DAKOTA. For a given set of input parameters, the growth model predicts the size corrosion product by carrying out an aging simulation. The results are then post-processed to yield the equivalent contact resistance. UQ analysis based on Latin Hypercube Sampling then generates a family of resistance curves. Based on engineering judgment, five input variables have been chosen as the uncertain parameters for this UQ analysis: temperature, hydrogen sulfide concentration, forward and reverse reaction rates, and diffusivity of copper vacancies. The span of contact resistance due to uncertainty in the parameters increases as age of the component increases. This information is useful in quantifying the reliability of aging electrical circuits.

MODELING OF NON-STATIONARY WINDS IN GUST-FRONTS

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A new approach to model the non-stationary features of winds in gust-fronts is presented. The non-stationary features in both time and frequency of winds in gust-fronts are captured utilizing the Wavelet transform and the Hilbert transform in conjunction with an empirical mode decomposition. The non-stationary winds are modeled as a sum of a time-varying mean and a fluctuation component described as a stationary random process. Both the Wavelet transform and the Hilbert transform combined with empirical mode decomposition can be viewed as a class of filter banks which can decompose a signal into band-pass component processes. Utilizing these transforms the gust-front winds are decomposed in terms of the time-varying mean wind and the fluctuating component. The lowest frequency filtered component represents the time varying mean and it is related to the traditional time averaged mean wind speed. It is noted that the fluctuating component representing the sum of the remaining filtered components adequately represents the statistical and spectral features that are similar to traditional stationary wind data. Data from Hurricane Lili, 2002 was utilized to obtain turbulence intensity, gust factors, power spectral density function and probability density function. It is noted that these statistical and spectral features are similar to those obtained using traditional analysis, but some discrepancies in the spectral and probabilistic descriptions are noted due to the contamination of the time varying mean in the traditional analysis. Detailed examples are presented, which also highlight the effectiveness scheme based on Wavelet or Hilbert transform. The proposed analysis framework provides a convenient mathematical framework for capturing salient features of non-stationary data and can be immediately extended for the dynamic analysis of systems under transient loading.

STOCHASTIC APPROACH TO MANAGE THE VARIABILITY FROM IN SITU DATA

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The response of soil to strong motion events is noticeably affected by its shear resistance as well as the input motion frequency content and duration. In numerical simulation of the dynamic local site response, attention is often focused on detailed descriptions of the dynamic properties of the soil investigated. Numerous types of in situ and laboratory tests can be employed to describe the dynamic parameters in elastic-equivalent simulations of local site response carried out by means of numerical codes such as Quad4M and ProShake. The seismic refraction method and the down-hole method are commonly used in the practice to estimate the in situ Vp and Vs values of the soft deposits overlaying the bedrock formation. Seismic refraction method measures seismic velocity values within a large part of deposits whereas the down-hole method evaluates local characteristic of soils. Often they are used together to dynamically characterize a site even if velocity from these tests provide scattered measures. In order to manage the uncertainties in a small amount of data from the preceding tests two strategies can be applied. The first one, assumed in a deterministic perspective, takes account of the variability in measurements as local heterogeneity which can be modeled by means of a set of sub-domain with different values of mechanical properties.

On the other hand, the uncertainties in measurements can be interpreted as the result of a long time natural processes that can be read by means of the stochastic approach (known as inherent variability of soil) and measurement errors. This is a framework where the scatter in measurements can be modeled and forecast as inherent spatial heterogeneities. This paper deals with the dynamic characterization of the site of Fivizzano by means of the preceding two in situ tests. The variability of data sets was treated to build a stochastic field model. Results from this study can be employed into a 1D dynamic simulation. Finally comparisons between travel-time curves built by means of deterministic and statistical techniques were shown.

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ESTIMATING SAMPLE AUTOCORRELATION FUNCTIONS USING BOOTSTRAP

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The autocorrelation function is fundamental to second-order characterization of random fields. However, the sampling properties of the sample autocorrelation function are extremely complicated and only approximate asymptotic results may be obtained. This paper develops a practical bootstrap technique for geotechnical engineers to obtain a more robust estimate of the autocorrelation function and to gain an appreciation of the underlying variability in the estimate with minimal assumptions. The proposed bootstrap technique can be briefly described as follows:

1. Let X(t) be a stationary real-valued process with zero mean and finite variance and {x1, x2, …, x_N} be the values sampled along one segment of one realisation of the process, i.e. where $x_k = x(t_k)$ and
   $t_k = k\Delta$, k = 1, 2, …, N. The discrete Fourier transform is:
   $$H(f_m) = \sum_{k=0}^{N-1} x_k \exp\left(\frac{2\pi ikm}{N}\right) \qquad (1)$$
   where frequency $f_m = m/(N\Delta)$ and m=-N/2, …, N/2. The sample spectral density function (two-sided) is:
   $$\hat{S}(f_m) = \frac{\Delta\,|\,H(f_m)\,|^2}{N} \qquad (2)$$
2. Compute an estimate of the spectral density function by smoothing $\hat{S}(f)$:
   $$\tilde{S}(f_m) = \frac{1}{2b+1}\sum_{k=-b}^{b}\hat{S}(f_{m+b}) \qquad (3)$$
3. For large N, Priestley (1981) showed that the ratio of $\hat{S}(f)/S(f)$ for m = 0, …, N/2 forms a random vector with independent components for Gaussian linear processes. More specifically, the random components are exponentially distributed with mean = 1 for m = 1, …, N/2-1 and chi-square distributed with one degree of freedom for m = 0 and N/2 (Nyquist frequency). This immediately suggests that bootstrap samples of the sample spectral density function can be generated as:
   $$\hat{S}*(f_m) = S(f_m)\varepsilon_m \qquad (4)$$
   where ε_m are independent random variables distributed as noted above. Because S(f) is not known, it is necessary to replace S(f) by $\tilde{S}$(f) in Eq. (4).
4. The last step is to perform inverse Fourier transform on each $\hat{S}$*(f) to obtain the corresponding sample autocorrelation function. Given a collection of bootstrap sample autocorrelation functions, it is easy to evaluate its mean, variance, and other sampling properties at each lag Tm using the usual method of moments.

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UNCERTAINTY AND RELIABILITY IN GEOMECHANICS: SESSION 1

CALIBRATION OF SOIL CONSTITUTIVE MODELS WITH HETEROGENEOUS PARAMETERS

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The mechanistic characterization of soils in the form of constitutive models is essentially an encapsulation of controlled experimental measurements into a format that hopefully enables extrapolation beyond the specific conditions that existed during calibration. Generally, soil constitutive models are calibrated from boundary measurements on laboratory soil specimens which are assumed to be homogeneous: characterization is then relegated to an average homogenized material, one that is “equivalent” to the actual heterogeneous one. While this approach has served mechanics well, it has not permitted the development of material models that are capable of reproducing the heterogeneity and variability typically observed in soils.

A method for soil model calibration that accounts for material heterogeneities has been developed, which utilizes full-field experimental measurements, thus accounting for the non-uniformity of response. Image-based displacement measurements of deforming triaxial specimens are assimilated into finite element predictive models of soil behavior. Model parameters are allowed to vary locally through an inversion process, until an optimal match between predicted and measured specimen shapes is obtained. The resulting distribution in model parameters provides an avenue to describe the inherent variability of the coarser-scale features of the soil, which are inherited from the micro-structural behavior. The stochastic characterization of soil properties is synthesized from an ensemble of such experiments. The method has performed successfully in conjunction with linear soil models, and is currently being extended to non-linear models.

ASSESSMENT OF WEAK STATIONARITY USING NORMALIZED CONE TIP RESISTANCE

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Weak stationarity or second-order statistical homogeneity is a prerequisite for geotechnical variability analyses. Non-parametric tests developed from independent data have been used in the geotechnical literature to assess weak stationarity. However, the underlying independence assumption contradicts the well known observation that spatially varying soil properties are correlated. This paper compares the assessment of weak stationarity using the classical non-parametric Kendall's tau test (KTT) and a modified Bartlett statistic (MBS) procedure that explicitly includes the correlation structure in the rejection criterion.

Because cone penetration test soundings are nearly continuous and carry low measurement errors, they are most useful for such a statistical study. A total of 70 geotechnically homogeneous soil units (HSU) from 304 CPT soundings were identified on the basis of normalized cone tip resistance (q_{c1N}) and normalized sleeve friction ratio. The identified HSUs cover a wide range of soil types (clays, silt mixtures, sand mixtures, sands). Hence, conclusions drawn in this study should be fairly general. Details of the stationarity tests, preliminary data preparation, trend removal techniques and autocorrelation function estimation procedures are given elsewhere (Uzielli, 2004).

Based on KTT, 57 out of the 70 HSUs were found to be stationary at a level of significance of 5%. To apply MBS, it is necessary to fit one of the following theoretical autocorrelation models (ACMs) to the observations: a) single exponential (SNX); b) cosine exponential (CSX); c) second-order Markov (SMK); and d) squared exponential (SQX). Considering only best-fit ACMs with highest R^2, 55 MBS-stationary q_{c1N} profiles were obtained at a level of significance of 5%. The SNX, CSX, SMK and SQX models provided the best fit in 5, 22, 16 and 12 cases, respectively. Phoon et al. (2003) observed that the stationarity rejection criterion is significantly dependent on the ACM employed. Hence, Uzielli (2004) set a minimum R^2 value of 0.9 for the ACM fit to be considered acceptable (this revised procedure is referred to as MBSR). Applying this stricter procedure, 41 data sets were found to be MBSR-stationary at 5% level of significance. Both KTT and MBSR agree in the majority of the cases. However, HSUs that are MBSR stationary are rarely not KTT-stationary. Conversely, there are a number of HSUs that are KTT-stationary, but not MBSR-stationary. If one assumes that MBSR provides more accurate stationarity assessments, then the power of KTT (rejecting the null when it is false) is lower, i.e. KTT is less discriminatory. Both KTT and MBS indicate that physical homogeneity does not always imply stationarity. More detailed studies are needed to clarify these preliminary observations.

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UNCERTAINTY AND RELIABILITY IN GEOMECHANICS: SESSION 1

CHARACTERIZATION OF NATURAL VARIABILITY OF HYDRAULIC PROPERTIES OF SOILS

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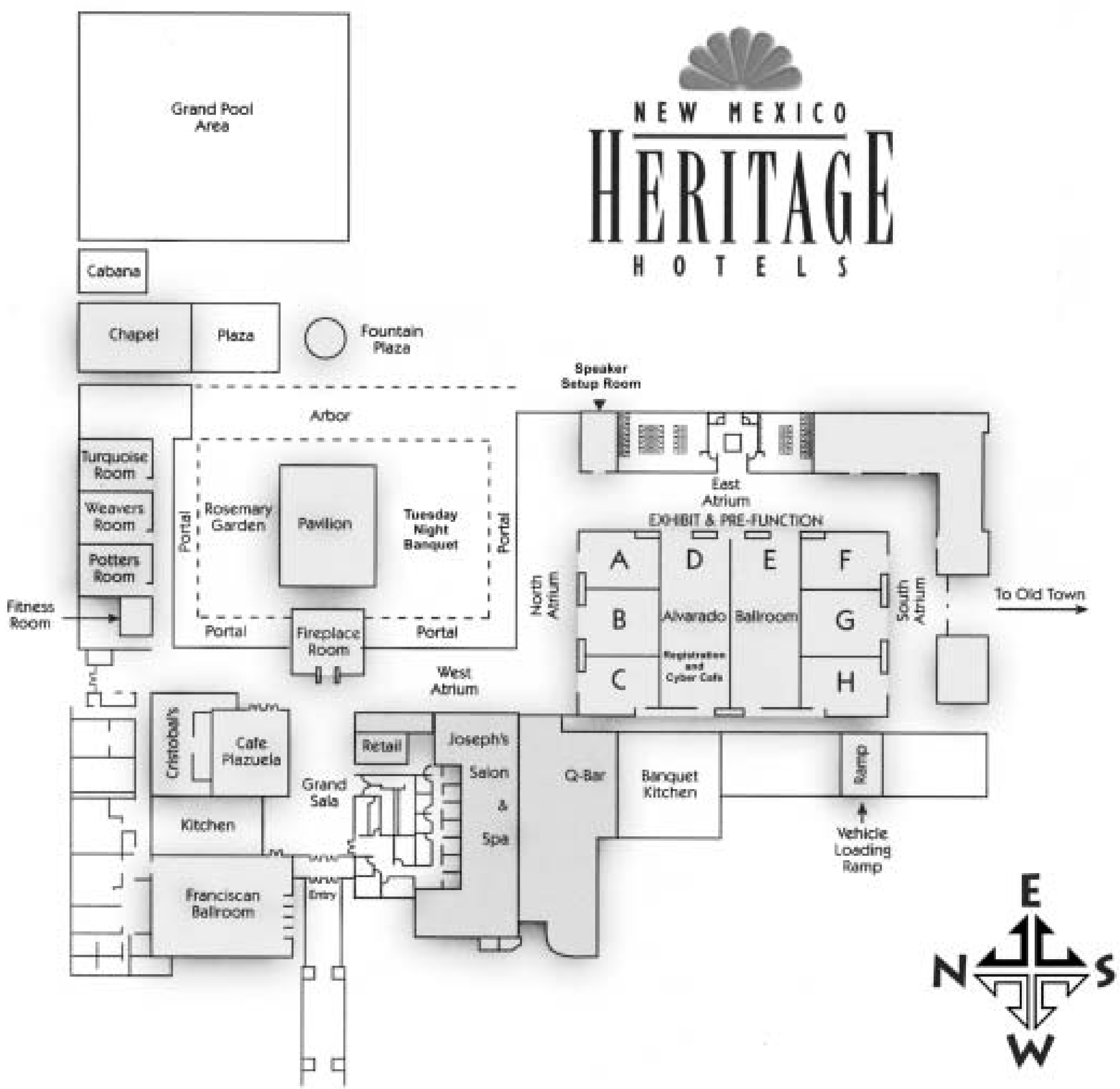
In forensic investigation of several slope failures in Hong Kong, many soil samples from each of the failed slopes were taken. It was found that the grain-size distributions of soil samples from any particular slope vary greatly. Together with variable soil densities and moisture contents, the soil samples within a site exhibit greatly variable hydraulic properties, such as spatially and temporally variable coefficient of permeability, pore water pressure and water content. The variability of these properties appears to be clueless.

This paper explores a method to characterize the variability in hydraulic properties of soils at one site. The soil at a spot is assumed to consist of two characteristic components with known grain-size distributions. Thus the seemingly random grainsize distributions of the soil samples can be described by a single variable, i.e., the proportion of the two characteristic components. The variability in the saturated permeability is related to the density and grain-size distribution of the soil. The special and temporal variation of the instant permeability and pore-water pressure are described by the water content and a soil-water characteristic curve of the soil. Thus, it is possible to consider the main features of hydraulic properties with three variables, i.e., the density, water content and proportion of characteristic components.



Grand Pool Area
NEW MEXICO HERITAGE HOTELS
Cabana
Chapel
Plaza
Fountain Plaza
Speaker Setup Room
Arbor
Turquoise Room
Weavers Room
Potters Room
Fitness Room
Portal
Rosemary Garden
Pavilion
Tuesday Night Banquet
Portal
Portal
Fireplace Room
Portal
East Atrium
EXHIBIT & PRE-FUNCTION
A
D
E
F
North Atrium
B
Alvarado Ballroom
G
South Atrium
To Old Town
C
Registration and Cyber Cafe
H
West Atrium
Cristobal's
Cafe Plazuela
Retail
Joseph's Salon & Spa
Q-Bar
Banquet Kitchen
Ramp
Grand Sala
Kitchen
Vehicle Loading Ramp
Franciscan Ballroom
Entry
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Monday Technical Program: 1:00 – 3:00 PM

ROOM	**Technical Session Title**
Ballroom A	Computational Methods: Session 2 *
Ballroom B	Probabilistic Life-Cycle Performance Assessment, Maintenance and Management of Aging Infrastructures: Session 2 *
Ballroom C	Probabilistic Methodology and Applications in Aerospace Engineering: Session 2 *
Ballroom F	Optimization Under Uncertainty: Session 1
Ballroom G	Stochastic Modeling in Aerodynamics and Aeroelastic/Hydroelastic Interaction *
Ballroom H	Uncertainty and Reliability in Geomechanics: Session 2 ^
Turquoise	Statistical Structural Health Monitoring +

** Sessions Organized by ASCE Probabilistic Mechanics Committee*
^ Sessions Organized by ASCE GI RAM
+ Sessions Organized by ASCE Probabilistic Mechanics Committee/ASME COUP

Technical Program: Monday, July 28: 1:00 – 3:00 PM				
Time 24 Min. Talks (* Speaker)	Room: Ballroom A **Computational Methods** **Session 2** Session Chairs: Johnson, E., Bergman, L.	Room: Ballroom B **Probabilistic Life-Cycle Performance Assessment, Maintenance and Management of Aging Infrastructures** **Session 2** Session Chairs: Frangopol, D., Ellingwood, B.	Room: Ballroom C **Probabilistic Methodology and Applications in Aerospace Engineering:** **Session 2** Session Chairs: Zhao, Z., Kurth, R.	Room: Ballroom F **Optimization Under Uncertainty** **Session I** Session Chairs: Mahadevan, S., Eldred, M.
1:00	Ensemble Uncertainty Quantification Wojtkiewicz, S.*	Modeling of Risk-Based Inspection, Maintenance and Life-Cycle Cost with Partially Observable Markov Decision Processes Corotis, R.*, Ellis, J. H., Jiang, M.	An Efficient Simulation-Based Method for Probabilistic Damage Tolerance Analysis with Maintenance Planning Shiao, M., Wu, J.*	Computational Efficiency in Reliability-Based Optimization Zou, T., Mahadevan, S.*
1:24	Stochastic Conditioner for Accelerating Convergence of Monte Carlo Simulations Desceliers, C.*, Ghanem, R., Soize, C.	Bayesian Reliability Updating Using System Identification Based on Selective Sensitivity Bucher, C.*	Application of a Microstructure-Based Fatigue Crack Growth Model to Probabilistic Life Prediction Enright, M.*, Chan, K., Kong, J.	Durability Based Robust Design Optimization for Fabricated Structures Kim, Y.*, Kyuba, H., Vik, T., Organ, D., Hurt, W.
1:48	Exact Expressions for the Variability Response Function of Stochastic Structural Systems and Corresponding Upper Bounds on Response Variability Papadopoulos, V., Deodatis, G.*, Papadrakakis, M.	On Reliability Assessment of Deteriorating Structural Systems Via Improved Monte Carlo Simulation Augusti, G.*, Ciampoli, M., Majorana, C.	Assessment of Modeling Uncertainties for Reinforced-Carbon-Carbon Debris Impacts Lyle, K.*, Fasanella, E.	An Efficient Reliability-Based Design Optimization Method Using a Single-Loop Approach Liang, J., Mourelatos, Z.*, Tu, J., Mahadevan, S.
2:12	Simulation of Non-Stationary Random Processes: A Wavelet and Hilbert Transforms Perspective Wang, L.*, Kareem, A.	Performance-Based Optimal Design of Structures Higuchi, S.*, Bucher, C.	Application of a Conditional Expectation Response Surface Approach to Probabilistic Fatigue Momin, F., Millwater, H.*, Osborn, W., Enright, M.	A Most Probable Point-Based Method for Reliability Analysis, Sensitivity Analysis, and Design Optimization Hou, G.*, Gumbert, C., Newman, P.
2:36	Simulation of Non-Gaussian Stochastic Vector Processes Chen, Y.*, Deodatis, G.	Performance-Based Design of Base Isolation Systems Using Inverse-Form van de Lindt, J.*, Drewek, M.	Artificial Neural Network Approach for Structural Reliability Analysis Deng, J.*, Gu, D.	

Technical Program: Monday, July 28: 1:00 – 3:00 PM				
Time 24 Min. Talks (* Speaker)	Room: Ballroom G **Stochastic Modeling in Aerodynamics and Aeroelastic/Hydroelastic Interaction** Session Chairs: Sarkar, A., Kijewski-Correa, T.	Room: Ballroom H **Uncertainty and Reliability in Geomechanics** **Session 2** Session Chairs: Phoon, K., Rechenmacher, A.	Room: Turquoise **Statistical Structural Health Monitoring** Session Chairs: Noori, M., Graham Brady, L.	
1:00	On Estimation of Empirical Orthogonal Modes in Inflow Turbulence for Wind Turbines Saranyasoontorn, K.*, Manuel, L.	Probabilistic Models for the Assessment of Post Cyclic Soil Deformations Cetin, K. O.*, Unutmaz, B.	A Statistical Pattern Recognition Paradigm for Structural Health Monitoring Farrar, C.*, Sohn, H., Park, G.	
1:24	Employing Sensitivity Derivatives to Estimate Uncertainty Propagation in CFD Putko, M.*, Newman, P., Taylor, A.	Model Uncertainty of a CPT-Based Simplified Method for Liquefaction Triggering Analysis Juang, C.*Yang, S.	Stochastic Evaluation of Bridge Control with Side Wings Hurtado, J.*, Alvarez, D.	
1:48	Variational Multiscale Stabilized FEM Formulations for Stochastic Advection-Diffusion Equations Badrinarayanan, V.*, Zabaras, N.	Seismic Liquefaction of 3D Randomly Variable Soils Popescu, R.*, Prevost, J. H., Deodatis, G.	Preliminary Study of a Bayesian Probabilistic System Identification Approach for Structural Health Management Cao, Y.*, Noori, M., Saadat, S., Hou, Z., Buckner, G., Masuda, A.	
2:12	Multivariate Stochastic Simulation of Wind Pressure Over Low-Rise Structures Masters, F.*, Gurley, K.	Probabilistic Slope Stability Under Seismic Loading Rahhal, M. E.*, Ghosn, R.	Bayesian Inference Applied to Structural Model Updating and Damage Detection Papadimitriou, C.*	
2:36	A Nonlinear Discrete Model for Wind-Excited Suspended Cables Carassale, L.*, Piccardo, G.	Quantification of Uncertainty Using Power Laws - A Geotechnical Perspective Rucker, M.*	Bayesian Analysis of the Phase II IASC-ASCE Structural Health Monitoring Experimental Benchmark Data Ching, J.*, Beck, J.	

ENSEMBLE UNCERTAINTY QUANTIFICATION

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This paper addresses the need for the development of uncertainty quantification algorithms that leverage information from one realization to another. Although the size of the computational models used in some weapons calculations is extremely large, i.e. millions of equations, the uncertainty to be analyzed is oftentimes very localized to small regions of the model. One example of this manifests itself in a study of the effects of damping in connections between structural dynamic subsystems. While the full analysis model for this system is on the order of million of degrees of freedom, the nodes involved in an uncertainty analysis of the connection is on the order of ten. Herein, initial efforts to explore, expand, and develop UQ methods that exploit this localization of uncertainty will be discussed.

Algorithms for linear algebraic systems have been developed and will be outlined here. In addition, their efficacy will be demonstrated through several examples. These algorithms utilize linear algebra techniques for low rank matrix updates, Sherman-Morrison-Woodbury formulas. The computational procedure consists of a small number of full system runs, the number of nodes involved in the connections in the abovementioned scenario. The solutions from this small number of runs are then used to construct a solution update procedure where the remaining computation for each realization involves a system solution of greatly reduced size. The ratio of the cost of each subsequent realization after these initial calculations to a full system solution is approximately on the order of the ratio of the number of degrees of freedom of the full system model to that involving uncertainty. Thus, one can expect speedups of several orders of magnitude for the subsequent realizations. In addition, the system updates, due to the small systems being solved, can be performed using a wider variety of computing resources.

It is forseen that the greatly increased number of realizations can be used to obtain greater fidelity in failure assessments (smaller failure probabilities) and/or to address the epistemic uncertainty issue by considering alternate plausible uncertainty models for the parameters being studied.

STOCHASTIC CONDITIONER FOR ACCELERATING CONVERGENCE OF MONTE CARLO SIMULATIONS

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A method is developed in this paper to accelerate the convergence in computing the solution of stochastic algebraic systems of equations. The method is based on computing, via statistical sampling, a polynomial chaos decomposition of a stochastic preconditioner to the system of equations. This preconditioner can subsequently be used in conjunction with either Chaos representations of the solution or with approaches based on Monte Carlo sampling. In addition to presenting the supporting theory, the paper also presents a convergence analysis and an example to demonstrate the significance of the proposed algorithm.

EXACT EXPRESSIONS FOR THE VARIABILITY RESPONSE FUNCTION OF STOCHASTIC STRUCTURAL SYSTEMS AND CORRESPONDING UPPER BOUNDS ON RESPONSE VARIABILITY

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Exact closed-form analytic expressions are established for the first time for the variability response function (VRF) of both statically determinate and indeterminate structures with uncertain properties modeled by stochastic fields (in past research, expressions for the VRF have been established using truncated series expansions). The response variance of such structures is expressed as the integral of the product of the VRF multiplied by the spectral density function of the stochastic field modeling the uncertain system properties over the wave number domain. The most important application of VRF's is in the establishment of spectral- and probability-distribution-free upper bounds on the response variability. These bounds require knowledge of only the variance of the random system properties and are realizable in the sense that it is possible to fully determine the stochastic field modeling the random system properties that produces them. The bounds hold for any magnitude of the variability of the uncertain system properties. They are particularly useful for practical applications because in most cases the only information available is the mean and variance of the stochastic field modeling the uncertain system properties. These bounds can also be computed numerically using a so-called Fast Monte Carlo Simulation (FMCS) procedure that makes this approach very general. Numerical examples are provided.

COMPUTATONAL METHODS: SESSION 2

SIMULATION OF NON-STATIONARY RANDOM PROCESSES: A WAVELET AND HILBERT TRANSFORMS PERSPECTIVE

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This paper presents simulation of nonstationary processes utilizing the Wavelet and Hilbert transforms. This study focuses on the time-frequency features of non-stationary processes, which are essential in capturing non-stationary characteristics in simulation schemes. Utilization of non-stationary processes in engineering design and research has significantly increased recently with the recognition of performance based design. The Wavelet transform and the Hilbert transform, with a prior empirical mode decomposition, lend themselves to a convenient simulation of non-stationary processes which is particularly suited to simulation based on given realizations of the target processes. The Wavelet transform facilitates time-frequency representation of the target signal in terms of a bank of wavelet coefficients. Through an empirical mode decomposition a signal can be expressed in terms of intrinsic mode functions, each amenable to a Hilbert transform thus providing a mapping in the time-frequency plane. These features may be manipulated through multiplication with a Gaussian white noise and respective inverse transforms couched in a Monte Carlo simulation framework. Additional schemes based on the amplitude and phase modulations, in the Wavelet and Hilbert Transforms context, are also discussed. Examples concerning the simulation of ground motion records are presented to demonstrate efficacy of these schemes.

SIMULATION OF NON-GAUSSIAN STOCHASTIC VECTOR PROCESSES

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Among the various methodologies developed to generate sample functions of stochastic vector processes, fields and waves for Monte Carlo Simulation studies, there still exists one challenge: to accurately represent the crossspectral density matrix for weakly-correlated vector components with highly-skewed non-Gaussian marginal pdf's. In this regard, this paper proposes an efficient spectral representation approach based on the concept of translation vector processes, which is capable of producing realizations of stationary, multivariate, non-Gaussian stochastic processes, given a prescribed target cross-spectral density matrix and marginal (non-Gaussian) probability distribution functions. The proposed methodology is an extension of the Popescu, Deodatis and Prevost iterative algorithm [1], through the use of empirical non-Gaussian cumulative distribution functions [2] of the underlying "Gaussian" field. The modified methodology first generates an underlying "Gaussian" vector field using FFT, and then maps it into the target normalized non-Gaussian field using a memoryless nonlinear probability filter in conjunction with an iterative scheme. In each iteration, the cross-spectral density functions are updated by using the auto-spectra and corresponding coherence functions to satisfy the positive definite requirement of the cross-spectral density matrix. Finally, the actual non-Gaussian sample process can be obtained easily from the normalized sample process according to the target mean and variance. The advantage of using an ergodic underlying Gaussian field over a non-ergodic one is also discussed. The limitations of the proposed methodology with respect to the level of deviation of the marginal pdf's from the Gaussian are carefully identified.

In order to demonstrate the efficiency and capabilities of this methodology, one numerical example and one engineering application example are presented in this paper: 1) simulation of a tri-variate, one-dimensional stochastic vector processes characterized with highly-skewed Lognormal, Gamma and Beta marginal probability distribution functions, and prescribed Kaimal power spectral density functions with Davenport coherence functions; 2) generation of non-Gaussian wind-induced pressure fields in the separated flow regions on a longspan bridge for different wind directions, where the target cross-spectral density matrix and marginal probability distribution functions are calibrated from wind tunnel experimental data. The obtained results indicate that the methodology is very promising and can accurately reproduce a wide range of highly-skewed non-Gaussian marginal pdf's, as well as the auto- and cross-spectral density functions in a sample-by-sample, as well as ensemble-average sense.

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MODELING OF RISK-BASED INSPECTION, MAINTENANCE AND LIFE-CYCLE COST WITH PARTIALLY OBSERVABLE MARKOV DECISION PROCESSES

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A formal decision model approach is taken to describe the deterioration and intervention process, for which current state and actions affect future structural performance. These future states evolve probabilistically, and inspection and consequent intervention must be projected in order to develop a dynamic decision process that projects lifetime optimal expected performance. The technique utilized in this paper is that of the Markov Decision Process (MDP), which is based on the application of sequential decision theory (dynamic programming) to the control of Markov chains. The application of this approach to problems for which the true states are known only to within a probabilistic certainty is referred to as the partially observable MDP.

In the partially observable MDP, observations of the process (i.e., inspections) form a vector **Y(t)**, which partially captures the true state of the core process through a relationship matrix, P[**Y|X**], in which **X** is the condition state of the true process. The approach taken in this study is to develop an information vector, **q(t)**, which is known to the decision maker at any time. It consists of all prior information, Bayesian updates based on the history of inspection results for the **Y** process, and state transformation probabilities based on all prior maintenance and repair actions. Because the information vector forms a Markov process, the decision process is solved using **q(t)** as an *equivalent MDP* problem.

All costs at each time step are brought back to current using present discounted value, after future outcomes, optimal actions and costs are computed by a Markov projection. Two major deterioration models are used: fatigue of steel girders and corrosion of steel reinforcing in concrete girders. A Markov deterioration process is developed for these processes and tested for stationarity. These deterioration processes are then combined with four inspection strategies and five maintenance strategies, all with separate costs and probabilistically-described results. The transition matrix of the structure at any time step consists of a combination of the no-action change due to applied loads and environmental effects, and the maintenance action.

With the ability to probabilistically project future state probabilities and costs, the present value effect of all decisions at a particular time step can be computed solving a finite horizon partially observable MDP. Optimal decisions can be made on a criterion such as minimum cost, for which costs include risk-based state costs. By including initial design as well as operating policies in the model, a lifetime optimal initial design can be selected, although the analytical models at the moment can only be solved for alternative initial designs by iteration. The procedures are illustrated by application to a steel girder composite highway bridge.

BAYESIAN RELIABILITY UPDATING USING SYSTEM IDENTIFICATION BASED ON SELECTIVE SENSITIVITY

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The assessment of structural reliability in the context of health monitoring or design re-evaluation must be base on a suitable probabilistic description of structural properties. During the life-span of a structure this amounts to observing relatively small changes of system properties. Due to their simplicity, measurements of dynamic responses are most suitable for permanent observations. These measurements have to be followed by the (statistical) estimation of parameter values for a given structural model [1].

Unfortunately, system identification usually leads to rather ill-conditioned mathematical problems. This tends to become more pronounced as the number of parameters to be identified increases. The concept of Selective Sensitivity ([2], [3]) allows a way out of this dilemma. Basically, this approach provides specific excitations which are quite sensitive to small number of parameters (which are identified) and rather insensitive to a large number of parameters (which are not identified). By suitable repetition of the procedure, all parameter values can be found. One of the major disadvantages of this approach is the requirement to have fairly good knowledge about the true values of *all* parameters.

However, this can actually be construed as an advantage for monitoring purposes where one is interested in rather small changes of the parameters, so that reasonably precise knowledge is already available. The paper will show how to concept can be extended to the case where prior knowledge on the system parameters is given in terms of probabilistic measures rather than in terms of deterministic quantities. This information will be utilized to:

a) Determine a suitable (i.e. selectively sensitive) excitation
b) Serve as prior for the Bayesian updating procedure

The final paper will demonstrate the applicability of this approach to the analysis of a multi-story frame structure.

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PROBABILISTIC LIFE-CYCLE PERFORMANCE ASSESSMENT, MAINTENANCE AND MANAGEMENT OF AGING INFRASTRUCTURES: SESSION 2

ON RELIABILITY ASSESSMENT OF DETERIORATING STRUCTURAL SYSTEMS VIA IMPROVED MONTE CARLO SIMULATION

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The reliability assessment of a structural system can be a very complex task in many cases, due to the uncertainty of the parameters governing the structural response and the computational effort required by a realistic modeling of the nonlinear structural behaviour, especially under accidental actions. This task is even more complex if the system is subject to deterioration in time due to ageing, and the service lifetime must be determined taking into account the effects of deterioration mechanisms and their interaction with those of the actions due to exposure and usage.

In this paper, an advanced simulation technique is analyzed. It consists in coupling Latin Hypercube Sampling with Simulated Annealing: the former is used as a tool to generate random samples of the input variables, while the latter is used to enforce the statistical correlation among the same variables [1][2]. The coupled technique has shown itself to be useful in assessing the reliability of complex structural systems subject to deterioration, when analytical models of the structural response are not available, and numerical computations are too cumbersome: indeed, in these cases pure Monte Carlo simulation cannot be applied, as it requires a large number of simulations (i.e. repetitive calculation of structural response).

Latin Hypercube Sampling is a special type of Monte Carlo numerical simulation, which uses the stratification of the cumulative probability distribution function (CDF) of each input variable. This simulation strategy has many advantages: it may be used with any CDF; it does not affect the statistical parameters of the input variables; it is simple and effective; the regularity of probability intervals ensures that the multi-dimensional space of random variables can be satisfactory covered even by a limited number of sampling points.

During sampling, an undesired correlation can be introduced between the random variables; on the other hand, there are cases in which a prescribed statistical correlation between each pair of random variables, as defined by the user-defined correlation matrix, must be introduced. The stochastic optimization technique denoted as Simulated Annealing has been adopted to solve this problem, that is to adjust random samples in such a way that the resulting correlation matrix is as close as possible to the target one.

As an example case, the procedure is applied to the reliability assessment of a pre-stressed concrete containment vessel, subject to sudden and severe changes of temperature and internal pressure, in order to evaluate the effects of ageing due to such shocks and the chance of prolonging the operational lifetime.

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PERFORMANCE-BASED OPTIMAL DESIGN OF STRUCTURES

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Optimal economic design of structures requires the minimization of all costs accumulated during their life-cycle. In other words, structures have to be designed in such a way, that the benefit gained from assuring usefulness, structural integrity and harmlessness to life and limb surpass the expenses spent on construction, maintenance, operation and, finally, demolition [1, 2]. But from this follows also, that an optimal economic design has to take into account simultaneously different optimization criteria like, e.g., sufficient serviceability and reliability against ultimate failure. Although there exist a few approaches in terms of multi-criteria optimization, these formulations are based in general on constraints only.

This paper proposes a framework for cost optimal design based on system reliability concepts with different performance criteria. The performance criteria considered herein are

• serviceability limit strains,
• partial failure of components and
• ultimate limit state, i.e., structural failure.

Costs for construction, failure, repair and non-serviceability are taken into account. Special emphasis is put on aspects of time-variant reliability analysis. The design framework is exemplified for a structure subjected to random loading. The sensitivity of the optimal design solutions with respect to the driving cost parameters is examined. Open questions concerning the resulting optimal design solutions in case of similarly important performance criteria are discussed.

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PROBABILISTIC LIFE-CYCLE PERFORMANCE ASSESSMENT, MAINTENANCE AND MANAGEMENT OF AGING INFRASTRUCTURES: SESSION 2

PERFORMANCE-BASED DESIGN OF BASE ISOLATION SYSTEMS USING INVERSE-FORM

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The concept of performance-based seismic design has been explored by researchers for over a decade and the implementation stage has begun. Structural reliability has served as the cornerstone for LRFD code calibration and can help significantly with performance-based seismic design calibrations. This paper presents the results of a numerical study to examine application of the inverse-first order reliability method (Inverse-FORM) to design a base isolation system for buildings, within the context of performance-based seismic design. In other words, given that a target structural reliability level is required for a particular structure, how does one select the properties, i.e. design, the base isolation system to ensure the desired reliability level to all possible earthquakes at that site? This is accomplished herein by decoupling the earthquake demand from the structural concept using a method known as the environmental contour procedure which is essentially inverse-FORM. The earthquake is described in terms of magnitude and site-to-source distance using readily available earthquake data and a ground motion attenuation function provides the link between the earthquake demand description and the structural concept. An illustrative example at a hypothetical location for a building having a fundamental period of vibration of 0.4 seconds prior to retrofit is presented.

Key Words
Structural reliability, Inverse-FORM, Environmental Contours, Base isolation systems, retrofit.

AN EFFICIENT SIMULATION-BASED METHOD FOR PROBABILISTIC DAMAGE TOLERANCE ANALYSIS WITH MAINTENANCE PLANNING

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In the last decade, several probabilistic methods and associated software have been developed for damage tolerance applications considering uncertainties and inspection planning. While each of the methods appear to work well for its intended damage scenario and uncertainty modeling, these methods are limited in their ability to solve general problems. Therefore, general and accurate methods are needed for damage tolerance analysis with maintenance planning under various uncertainties, including initial flaw size and location, material properties, loads and environmental effects, inspection schedules, probability of detection (POD), and repair quality.

Monte Carlo simulation (MCS) offers the most robust and reliable solution framework for general problems. The only, but major, issue is that MCS is usually time-consuming. For maintenance optimization, the computational issue is further amplified because the conventional approach requires an MCS for each different maintenance plan. As a result, many sets of MCS are required to search for the optimal solution by exploring the design space that consists of many possible combinations of inspection scheduling, techniques, and repair/replacement/retirement strategies.

To relieve the computational burden in generating crack growth histories for many sets of MCS, this paper proposes an efficient method that combines the generality of MCS with the efficiency of analytical probabilistic methods. The core of the method is a recursive probabilistic integration (RPI) algorithm that allows repeated use of baseline MCS-based crack growth histories for various maintenance plans. The fundamental concept of RPI is based on branching out the probable events after each maintenance following an inspection where POD is applied. The probability of occurrence of each branched event is then determined based on the probability of crack detection. In addition to allowing the reuse of crack growth histories, RPI has an additional benefit of improving the MCS sampling efficiency, especially when a maintenance plan significantly reduces the probability of failure.

The RPI method has a wide range of applications because it can be applied to various damage scenarios, detection techniques, failure requirements, definitions of probability of failure, etc. The application area could include corrosion and composite damage. It is suitable for optimal inspection scheduling with reliability and cost consideration. It can also be used to verify new probabilistic methods or provide error-checking to ensure the reliability of failure prediction.

PROBABILISTIC METHODOLOGY AND APPLICATIONS IN AEROSPACE ENGINEERING: SESSION 2

APPLICATION OF A MICROSTRUCTURE-BASED FATIGUE CRACK GROWTH MODEL TO PROBABILISTIC LIFE PREDICTION

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The design of fatigue resistant materials is commonly performed independent of the design of individual components. The obvious drawback to this approach is that the material scientist has no information regarding the sensitivities of various material parameters to the probability of fracture associated with a particular component. One of the contributing factors to this problem is that most existing crack growth models are not linked with the fundamental material parameters; instead they are based on empirical constants obtained from curve fits of data from physical tests. Although these models characterize the main descriptors (mean, variance) of crack growth rate *da/dN* as a function of stress intensity factor *K*, they provide little or no physical insight into the material parameters that influence failure associated with fatigue crack growth.

A recent microstructure-based fatigue crack growth model [1,2] provides a relationship between material parameters and fatigue crack growth that can be used to establish a link between materials design and structural/mechanical component design. The model relates material parameters (e.g., dislocation cell size, dislocation barrier spacing, yield stress, fatigue ductility, Young's modulus) to fatigue crack growth rate da/dN, and is expressed as a closed form sum of terms representing all three stages (Stage I, II, III) of fatigue crack resistance. A probabilistic model [3] has been developed that quantifies crack growth rate variability as a function of stress intensity factor *K* that can be directly applied to probabilistic fatigue life prediction.

In this paper, the microstructure-based fatigue crack growth model is reformulated in terms of crack growth life and combined with additional random variables (e.g., defect size, applied stress, inspection, etc.) for application to probabilistic life prediction. The approach is illustrated for Titanium- and Nickel-based gas turbine engine components. The influences of various microstructural parameters on crack growth life variability and associated fracture probability is quantified for the range of available data. Stochastic model results are compared to existing experimental fatigue crack growth data to illustrate the feasibility of the approach.

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ASSESSMENT OF MODELING UNCERTAINTIES FOR REINFORCED-CARBON-CARBON DEBRIS IMPACTS

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The current literature shows a substantial variance in the stress-strain relationship for Reinforced-Carbon-Carbon (RCC) materials such as that used in the space shuttle leading edge. The purpose of this paper is to document the range of responses resulting from the material modeling uncertainty and to use sensitivity results to identify the material modeling parameters most likely to affect the response. The probabilistic analyses utilize two commercial codes - Matlab and LS-Dyna. Matlab scripts are used to control the simulation inputs. The initial analyses used 500 Monte Carlo simulations. The impact simulations are performed using LS-Dyna, a widely used, nonlinear, transient dynamic, finite element code. The LS-Dyna simulations replicate ballistic tests of RCC beams performed at NASA Glenn Research Center as part of the Columbia Accident Investigation. Specifically, RCC beam specimens were impacted by foam cylinders at velocities ranging from 400 to 700 ft/s. The RCC material was modeled in LS-Dyna using Material # 58 (Mat_laminated_composite_fabric). Twelve material input parameters have been incorporated in the probabilistic analyses. All post-processing is conducted in Matlab. In summary, the paper will describe the results of probabilistic analyses applied to foam impacts onto RCC beam coupons. The results of the probabilistic analysis will be compared with experimental results. In addition, the material property parameters controlling the response will be identified.

PROBABILISTIC METHODOLOGY AND APPLICATIONS IN AEROSPACE ENGINEERING: SESSION 2

APPLICATION OF A CONDITIONAL EXPECTATION RESPONSE SURFACE APPROACH TO PROBABILISTIC FATIGUE

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Specialized probabilistic analysis computer codes have been developed that are tailored to a particular application such as aerospace, nuclear, or off-shore structures. These types of tools contain specific mechanics models random variables and probabilistic methods and are highly optimized.

It is inevitable that over time the tools need to be expanded which is typically done by the original developer. However, sometimes the analyst, not the developer, wishes to expand the application of the program and does not have access to the source code. For example, the analyst wants to consider a variable as random that is deterministic in the original code.

In this paper we discuss the application of a conditional expectation probabilistic method combined with a response surface model to expand the random variables that the analyst can consider *without* modifying the original probabilistic code. As an example, the methodology is demonstrated using the DARWIN® probabilistic fatigue code for gas turbine engine disks and rotors.

The focused set of random variables in DARWIN, initial crack size, life scatter, probability of detection, etc., is expanded to include variables affecting the gas turbine disk stress distribution such as disk rotational speed. In effect, the total random variables considered is partitioned into two groups – those contained within DARWIN, addressed by DARWIN's probabilistic algorithms, and those outside DARWIN. The probabilistic analysis considering *all* random variables is computed by conditional expectation with the DARWIN probability of failure approximated by a response surface. This analysis involves coupled finite element analysis and probabilistic fatigue. The methodology is applied to a simple analysis for which a comparison solution is known and an more realistic engineering analysis.

ARTIFICIAL NEURAL NETWORK APPROACH FOR STRUCTURAL RELIABILITY ANALYSIS

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Monte Carlo simulation (MCS), first-order reliability methods (FORM and second-order reliability methods (SORM), are the most commonly-used reliability analysis methods. When the performance functions are implicit or multi-variate complicated, especially in case of the finite element method involved, such repetitive computation (in MCS) may be cumbersome. The computation of the function values and partial derivatives may be very difficult and time-consuming because of the iteration algorithm involved in FORM and SORM.

This paper uses artificial neural network (ANN) technique to simultaneously calculate the values and partial derivatives of the complicated performance function with little efforts and without affecting the accuracy. The proposed ANN-based reliability analysis method is to construct an ANN to approximate the performance function. Then large number of the performance function values can be easily available from the trained ANN generalization. First-order and second-order partial derivatives can also be computed using the successful trained ANN. FORM and SORM can then be applied not only to calculate the probability of failure but also to obtain the design point or checking point. Three examples were presented and the results of the new approach were compared to those obtained by conventional reliability methods such as the direct Monte-Carlo simulation, response surface method.

Key words
Reliability analysis; Artificial neural network (ANN); Implicit performance function; Finite Element Method; Probability of failure

COMPUTATIONAL EFFICIENCY IN RELIABILITY-BASED OPTIMIZATION

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During reliability-based optimization, reliability analysis is required during each iteration of the optimizer in order to evaluate reliability constraints. (Additional analysis may also be required to evaluate the derivatives of the reliability constraints when gradient-based optimization algorithms are used.) Reliability analysis is also an iterative process; so traditional reliability-based optimization is a nested loop analysis (i.e. a reliability analysis loop nested within optimization). As a result, the computational effort is prohibitive, especially when the optimum design has to satisfy a number of reliability constraints and the function evaluations are time consuming. Therefore, approaches are being pursued to achieve computational efficiency by decoupling the reliability and optimization iterations.

Currently available decoupling approaches are limited to application with the inverse first-order reliability method. In this paper, we develop an alternative decoupling approach to solve problems where FORM-based reliability analysis is infeasible and other methods, including Monte Carlo simulation, need to be used. The proposed approach is based on re-writing the reliability constraints using a Taylor series approximation. The reliability analysis provides the failure probability estimates and the derivatives for the approximated reliability constraints and makes them deterministic. This approach is able to include different reliability methods for different reliability requirements as dictated by the needs of accuracy, computational efficiency, and feasibility. The proposed methodology is illustrated with several example applications to automotive systems.

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DURABILITY BASED ROBUST DESIGN OPTIMIZATION FOR FABRICATED STRUCTURES

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With conventional finite element based structural optimization methods, the structural fatigue life cannot be defined as objective or constraints explicitly. The constraints are usually defined by the upper limits of stresses in critical locations based on the designer's intuition and experience along with some factor of safety, and the life of the optimized design is evaluated by the fatigue life analysis afterward. If the design is over-designed or under-designed compared to the target design life, the optimization process would be iterated with the modification of stress constraints. Multi-level optimization approaches are straightforward methods to automate the iterative design process with external optimizer. However, it requires prohibitively expensive computational time with the increase of the structural model size in practice.

Recently proposed durability limit stress approach [1] provides a method that considers structural fatigue life in design optimization directly according to the expected uncertainties in service loads, weld/connection types, material characteristics and finite element modeling. The durability constraints are obtained in the form of stress from the durability limit state equation so that they can be used directly in the finite element based optimization procedure. The durability limit state is defined based on the linear damage model, which is the function of stress ranges and the number of cycles corresponding to each stress range in the variable amplitude load histories.

The method is derived from the conventional reliability based optimization description, and is applicable to both stress-life and strain-life fatigue damage models with variable amplitude loads for designs involving long life. Since the reliability analysis is decoupled from finite element based optimization procedure, the computationally expensive finite element analysis based function evaluation is required just once during the whole reliability analysis iterations. The proposed method's validity on the prediction of fatigue design life under variable amplitude loads will be discussed with fabricated design examples.

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AN EFFICIENT RELIABILITY-BASED DESIGN OPTIMIZATION METHOD USING A SINGLE-LOOP APPROACH

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Reliability-Based Design Optimization (RBDO) can provide optimum designs in the presence of uncertainty in the design variables, parameters and simulation models. It can therefore, be a powerful tool for design under uncertainty. The traditional, double-loop RBDO algorithm requires nested optimization loops, where the design optimization (outer) loop, repeatedly calls a series of reliability (inner) loops. Due to the nested optimization loops, the computational effort can be prohibitive for practical problems. A single-loop RBDO algorithm is proposed in this paper. Its accuracy is the same with the double-loop approach and its efficiency is almost equivalent to deterministic optimization. It collapses the nested optimization loops into an equivalent single-loop optimization process by imposing the Kuhn-Tucker optimality conditions of the reliability loops as equivalent deterministic equality constraints of the design optimization loop. It therefore, converts the probabilistic optimization problem into an equivalent deterministic optimization problem. Several numerical applications including an automotive vehicle side impact example, demonstrate the efficiency and accuracy of the proposed single-loop RBDO algorithm.

A MOST PROBABLE POINT-BASED METHOD FOR RELIABILITY ANALYSIS, SENSITIVITY ANALYSIS AND DESIGN OPTIMIZATION

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Sampling and approximate integration are two commonly used approaches for reliability analysis. The Monte Carlo simulation plays a key role in the sampling approach, whereas the Most Probable Point (MPP)-based method plays a key role in the approximate integration approach. Derivatives of quantities resulting from reliability analysis can be computed by either the sampling approach or the approximate integration approach. Many works in reliability engineering, particularly in reliability-based design optimization, have given special attention to study the related derivatives. However, some of these derivatives are computed according to the functional relationship defined by the limit-state equation. Such derivatives are called behavior derivatives. Since the MPP can be obtained as a result of an optimization process, the probabilistic derivatives can also be viewed as the derivatives of the optimal solution or optimum sensitivity derivatives. In other words, the computation of such derivatives should involve not only the function of the limit-state equation but also the Kuhn-Tucker Necessary Conditions at the MPP.

The main goal of this work is thus to present a procedure that computes the probabilistic derivatives as derivatives of an optimal solution. Examples are used to demonstrate the application of such optimum sensitivity derivatives to form better procedures for reliability analysis and reliability-based design optimization (RBDO). First, we review the procedure to derive optimum sensitivity derivatives and to perform the reliability analysis. Then, we derive the sensitivities for two approximate integration methods; i.e., the Reliability Index Approach (RIA) and the Performance Measurement Approach (PMA). Sensitivity analysis of the PMA shows that its results are independent of the means and standard deviations of the problem random variables. This interesting result leads to the development of a new RIA, called PMAbased RIA (PRIA). Numerical verifications are given via several examples. Both convex and concave algebraic examples and a multidisciplinary flexible wing example are used to demonstrate the use of the newly devised method for reliability analysis. Our numerical experience shows that the PRIA method is robust and accurate; however, it is not as efficient as the conventional RIA for smoother limit-state equations. An initial attempt is also made in an RBDO procedure to first identify the active constraints by using PMA and then calculate their reliabilities and sensitivities by using the PRIA. This procedure is successfully demonstrated on a simple example.

ON ESTIMATION OF EMPIRICAL ORTHOGONAL MODES IN INFLOW TURBULENCE FOR WIND TURBINES

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An understanding of the inflow turbulence spatial structure is important in decisions related to siting of wind turbines. This study proposes the use of Proper Orthogonal Decomposition (POD) of the most energetic modes that characterize the spatial inflow random field describing the turbulence experienced by a wind turbine. The appeal for the use of POD techniques is that preferred spatial “modes” or patterns of wind excitation can be empirically developed using data from spatial arrays of sensed input/excitation. These loading modes explain in part the behavior of dynamic systems in an analogous way to how natural modes of vibration associated with response and developed using structure mass, stiffness, and damping properties can explain the same though again only in part. Proper orthogonal decomposition has generated much interest in wind engineering applications in recent years, albeit mainly for buildings, not for wind turbines. This study seeks to extend thinking related to this heuristically appealing approach to describing inflow by first examining the orthogonal subprocesses derived from a POD analysis defined by theoretical power spectra and coherence models commonly used for wind turbines. Then, based on field data from a wind turbine, estimates of cross-power spectral density functions are used to estimate empirical POD modes that are compared with those based on theoretical considerations. Accuracy in predicting power and coherence spectra from a limited number of POD modes is discussed.

EMPLOYING SENSITIVITY DERIVATIVES TO ESTIMATE UNCERTAINTY PROPAGATION IN CFD

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Two methods that exploit the availability of sensitivity derivatives are successfully employed to predict uncertainty propagation through Computational Fluid Dynamics (CFD) code for an inviscid airfoil problem. An approximate statistical second-moment method and a Sensitivity Derivative Enhanced Monte Carlo (SDEMC) method are successfully demonstrated on a two-dimensional model problem. First-and second-order sensitivity derivatives of code output with respect to code input are obtained through an efficient incremental iterative approach. Given uncertainties in statistically independent, random, normally distributed flow parameters (input variables); these sensitivity derivatives enable one to formulate first-and second-order Taylor Series approximations for the mean and variance of CFD output quantities. Additionally, incorporation of the first-order sensitivity derivatives into the data reduction phase of a conventional Monte Carlo Simulation allows for improved accuracy in determining the first moment of the CFD output. Both methods are compared to results generated using a conventional Monte Carlo method. The methods that exploit the availability of sensitivity derivatives are found to be valid when considering small deviations from input mean values.

VARIATIONAL MULTISCALE STABILIZED FEM FORMULATIONS FOR STOCHASTIC ADVECTION-DIFFUSION EQUATIONS

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An extension of the deterministic variational multiscale approach with subgrid scale modeling is considered for developing stabilized finite element method formulations for the stochastic advection and the incompressible stochastic Navier-Stokes equations. The stabilized formulations are numerically implemented using the spectral stochastic formulation of the finite element method. Wiener polynomial chaos and Karhunen-Loéve expansion techniques are used for representation of uncertain quantities. The proposed stabilized methods have been tested against various standard advection-diffusion and fluid flow examples with uncertainties in initial conditions, inlet boundary conditions and material properties.

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MULTIVARIATE STOCHASTIC SIMULATION OF WIND PRESSURE OVER LOW-RISE STRUCTURES

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The prescriptive measures for the design of structures to resist wind loads are under continual refinement as wind-tunnel, full-scale, and computational methods improve our understanding of wind-structure interaction. The database assisted design (DAD) concept now under development will offer an online database of wind load time histories and has the potential to further enhance load definitions. Several university-affiliated wind tunnel facilities have been contracted to generate an extensive library of such time histories for a large variety of building shapes and terrains. These physical testing efforts will be complemented by computational load generating methodologies including computational fluid dynamics and stochastic simulation. The intent is to use these means to extend existing records, and to interpolate/extrapolate between shapes tested in the wind tunnels. This paper focuses on the development of stochastic simulation algorithms for the generation of wind loads in separated flow regions, which are highly non-Gaussian.

Accurate stochastic simulation of extreme wind loading on a bluff body requires a method capable of simulating hundreds of correlated pressure time series, each possessing unique probabilistic and spectral contents. This paper utilizes multivariate simulation techniques to generate simultaneous pressure time histories at multiple locations, while preserving the marginal probability distribution function and spectral content at each location as well as the linear relationship among locations as described by the cross-power spectral density functions. The accuracy of the method is verified through comparison with wind tunnel data sets using both individual taps and multiple aggregate loading scenarios. The efficiency and limitations of the algorithm are discussed. Additionally, a method to interpolate wind tunnel data sets between shapes tested in the wind tunnel is investigated.

A NONLINEAR DISCRETE MODEL FOR WIND-EXCITED SUSPENDED CABLES

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The study of the dynamic behavior of cables has received a great attention in the last decades. The motion of cables is ruled by a set of nonlinear, partial-differential equations whose solution is usually tackled adopting deterministic approaches that imply drastic simplifications in the expression of the external excitation. In the case of wind-excited cables, a realistic modeling of the external load should involve the probabilistic nature of the atmospheric turbulence and the analysis of the response should be studied through the techniques of stochastic mechanics.

In the present paper the nonlinear discrete model of a cable excited by a turbulent wind is proposed. An arbitrary number Nx of structural modes and Ny of wind modes (Carassale and Solari 2002) can be included, obtaining a system of 2×Nx first-order ordinary differential equations driven by a vector of Ny independent random processes. Nonlinearities and parametric-excitation terms deriving from fluid-structure interaction are fully taken into account.

Preliminary results on the convergence of the modal expansion are investigated through the application to a realistic model of suspended cable. The probabilistic response is determined by the Monte Carlo simulation method and is analyzed studying its power spectral density (PSD) function and its probabilistic density function (pdf). The first examples highlight as higher modes can slightly modify the PSD and the pdf of the response, especially as regards in-plane motion, but they do not introduce any qualitative difference.

Therefore, the proposed non linear discrete model appears able to reproduce the random oscillations of suspended cables subjected to a bi-dimensional turbulent wind. Further advances in this analysis are represented by studying of simplified models in order to understand the importance of the three classes of nonlinear terms appearing in the cable equations (nonlinear direct excitation of turbulence, nonlinear aerodynamic damping, parametric excitation; Carassale and Piccardo 2004). Different cable models
characterized by mechanical and aerodynamical parameters varying within wide ranges are presently under investigation.

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PROBABILISTIC MODELS FOR THE ASSESSMENT OF POST CYCLIC SOIL DEFORMATIONS

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A Bayesian framework for probabilistic assessment of post cyclic deformations is described. A database, consisting of cyclic laboratory test results including cyclic shear strains as well as post cyclic volumetric strains, in conjunction with relative density, number of stress (strain) cycles and "index" test results is used for the development of probabilistically-based post cyclic deformation correlations. The proposed stochastic model allows full and consistent representation of all relevant uncertainties, including (a) model imperfection, (b) statistical uncertainty, and (c) inherent variabilities. Different sets of volumetric and shear strain boundary curves are developed for the assessment of post cyclic deformation problem, representing various sources of uncertainty that are intrinsic to the problem. The resulting correlations represent a significant improvement over prior efforts, producing predictive relationships with enhanced accuracy and greatly reduced overall model uncertainty.

UNCERTAINTY AND RELIABILITY IN GEOMECHANICS: SESSION 2

MODEL UNCERTAINTY OF A CPT-BASED SIMPLIFIED METHOD FOR LIQUEFACTION TRIGGERING ANALYSIS

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Case histories of soil liquefaction/no-liquefaction from recent earthquakes at sites that were investigated previously using Cone Penetration Test (CPT) are analyzed for their reliability indices and conditional probabilities of liquefaction. The focus of the study is to explore the use of First Order Reliability Method (FORM) for determining the reliability index and the conditional probability of liquefaction. In particular, the uncertainty of the Juang model [1], a simplified CPT-based model for liquefaction resistance and potential evaluation, is investigated for its model uncertainty in the framework of FORM. The uncertainties of the parameters used in the Juang model are also examined. The model uncertainty is estimated by calibration with a fairly large set of case histories. This calibration process involves extensive reliability analyses first without considering model uncertainty, which is used as a reference, then with various "trial" model uncertainties. When the model uncertainty is not considered in the reliability analysis, the probability of liquefaction is interpreted using a Bayesian mapping function that was established based on case histories [2]; when the model uncertainty is considered in the reliability analysis, the probability is simply obtained from the notional concept. The best estimate of the model uncertainty is determined by matching the probability from the Bayesian mapping function with the notional probability. The results show that the uncertainty of the Juang model may be characterized with a mean-to-nominal ratio of 1.05 and a coefficient of variation of 0.20 based on the case histories examined.

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SEISMIC LIQUEFACTION OF 3D RANDOMLY VARIABLE SOILS

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Previous studies concluded that small scale heterogeneity greatly affects the liquefaction potential of saturated soil deposits and provided geotechnical design guidelines to account for effects of various characteristic of spatial variability. All those studies were based on two-dimensional analyses of soil liquefaction (in a vertical plane) assuming plane strain behavior. Therefore, the correlation distance of soil variability in a direction normal to the plane of analysis was implicitly taken as infinite (i.e. no variability in the third direction).

In this study, a Monte Carlo simulation approach involving generation of sample functions of non-Gaussian random fields and nonlinear finite element analyses is used to investigate the effects of soil heterogeneity on the liquefaction potential of a "stochastically heterogeneous" soil deposit subjected to seismic loading. To assess the 3D effects, Monte Carlo simulation results obtained for a 3D soil deposit are compared with corresponding results from 2D plane strain analyses. The calculations are performed for a range of seismic acceleration intensities and the results are presented in terms of fragility curves expressing the probability of exceeding a certain degree of damage as a function of earthquake intensity.

UNCERTAINTY AND RELIABILITY IN GEOMECHANICS: SESSION 2

PROBABILISTIC SLOPE STABILITY UNDER SEISMIC LOADING

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Slope stability is of major interest in geotechnical engineering worldwide. In Lebanon, dealing with slope stability problems is very frequent. Our concern in the present research is to contribute to the understanding of certain aspects of slope stability by means of the reliability theory and to highlight the importance of the variability of soil properties in geotechnical calculations. The engineers resort to an approach by factor of safety to reduce the risk of failure. However, the approach of the safety factor cannot measure the probability of failure, or the level of risk related to a particular design situation. This new understanding of safety is associated with failure risk estimation by a mathematical relative probability. In fact, the calculated probability allows taking into consideration the statistical scatter of geotechnical as well as geometrical properties of slopes. A key aspect that is investigated is the application of the reliability theory to the limit equilibrium analysis. The importance of considering uncertainties is outlined when comparing probabilistic and deterministic calculations.

A probabilistic model for the analysis of seismic slope stability was developed. Traditional deterministic equations of Bishop and Culmann were improved by adding seismic loads. Based on the simulation of Monte Carlo, the distribution of each input parameter was used with the deterministic performance equations to produce a probability distribution of the result of the analysis. The allowed risk criterion was then applied to the distribution of output to choose the design parameters that have an acceptable level of risk. The probabilistic method developed in this research was applied to two cases. The first case study used the modified Culmann method for a finite slope with planar failure surface. The second case study was the application of the Bishop method for a finite slope with circular failure surface, by using response surface analysis method combined with a Monte Carlo simulation. For each case study, seepage and seismic analysis were considered. Cohesion, friction angle and unit weight were considered as random variables. As far as sensibility analysis is concerned, the friction angle proved to be the predominant variable in seismic slope stability problems. The effect of the correlation between cohesion and friction angle was also analyzed. A significant change in the probability of failure was measured for correlation coefficient values between –0.2 and –0.8 depending on seepage and seismic loading conditions. Finally, abacuses giving the probability of failure and reliability index were developed according to this methodology.

Consequently, it is essential to develop a risk-based design process that the engineers can use to combine the practical experience, the judgment, and the statistical data in order to analyze the stability of a slope for an allowable risk criterion.

QUANTIFICATION OF UNCERTAINTY USING POWER LAWS – A GEOTECHNICAL PERSPECTIVE

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An essential facet of geotechnical and geological engineering is understanding, characterizing and quantifying networks or systems of natural materials or phenomena and their behavior. Insights, understanding and practical applications may often be possible using conceptual mathematical and scientific breakthroughs that incorporate power-law relationships such as fractals and self-ordered criticality (SOC). Where a soil or rock mass is considered to be disordered systems or networks composed of many particles of different sizes, these concepts are especially useful. Using Zipf's Law, size-frequency distributions, where relatively smaller pieces or occurrences are more frequent than larger pieces or occurrences. Plotted logarithmically, with (event or particle) size on the abscissa (x-axis) and (number or frequency of) occurrence of the ordinate (y-axis), the resulting size-frequency trends tend to plot as approximately straight lines (power laws). However, there are usually at least two identifiable power law trends. The trend of the smaller size or event with larger frequency has a slope absolute value typically less than the dimension of the measurement. For a one-dimensional scan line or time, the slope absolute value would be less than one. For a 3-dimensional particle size distribution, the slope absolute value would be less than 3. This portion of the plot may be defined as fractal and reflects an essentially infinite supply of particles or events. At a certain size on the x-axis, the power law slope abruptly steepens for the larger size or event behavior at smaller frequency. This characteristic length or size reflects a scale at which the physics of the disordered system or network changes. If the slope absolute value is greater than the dimension of the system measurement, then a non-infinite supply of particles or events are indicated. Even though that behavior may plot as a power-law, it is non-fractal. The scale at the characteristic size can measure where the physics or behavior of a system changes or has changed. Knowledge of this characteristic size can provide significant insight into the behavior and apparent uncertainty of a system or network.

A well known practical application of these concepts is the Gutenberg-Richter earthquake magnitude-frequency relationship. Random vibrations encountered in geotechnical engineering, including traffic and industrial vibration, can follow a similar pattern. Other relationships exist in materials or events in geotechnical engineering. Particle size distributions often exhibit this behavior. Defining a trend for the sizes and frequencies of the largest particles permits making rational estimates of very large particle sizes at rare frequencies for excavation purposes. These applications, with examples, will be reviewed.

A STATISTICAL PATTERN RECOGNITION PARADIGM FOR STRUCTURAL HEALTH MONITORING

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The process of implementing a damage detection strategy for aerospace, civil and mechanical engineering infrastructure is referred to as *structural health monitoring (SHM)*. Here *damage* is defined as changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance. The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health. For long term SHM, the output of this process is periodically updated information regarding the ability of the structure to perform its intended function in light of the inevitable aging and degradation resulting from operational environments. After extreme events, such as earthquakes or blast loading, SHM is used for rapid condition screening and aims to provide, in near real time, reliable information regarding the integrity of the structure.

Our approach is to address the SHM problem in the context of a statistical pattern recognition paradigm[1]. In this paradigm, the process can be broken down into four parts: (1) Operational Evaluation, (2) Data Acquisition and Cleansing, (3) Feature Extraction and Data Compression, and (4) Statistical Model Development for Feature Discrimination. When one attempts to apply this paradigm to data from real world structures, it quickly becomes apparent that the ability to normalize data to account for operational and environmental variability is a key implementation issue when addressing Parts 2-4 of this paradigm. The authors believe that all approaches to SHM can be cast in the context of this statistical pattern recognition paradigm.

Although this paper will discuss each portion of the SHM process, particular attention will be paid to the statistical modeling portion of the paradigm. This portion of the structural health monitoring process has received the least attention in the technical literature{2,3]. The algorithms used in statistical model development usually fall into three categories and will depend on the availability of data from both an undamaged and damaged structure. The first category is group classification, that is, placement of the features into respective "undamaged" or "damaged" categories in a discrete manner. Analysis of outliers and density estimation is the second type of algorithm. The third category is regression analysis. This analysis refers to the process of developing a continuous function that correlates data features with particular types, locations or extents of damage. Also, the concepts of "supervised" and "unsupervised" learning will be discussed as they pertain to the SHM problem. Results from various damage detection studies performed at Los Alamos National Laboratory will be used to illustrate the various portions of the statistical pattern recognition paradigm.

The presentation will conclude with a brief introduction to damage prognosis, which is the process of predicting the remaining system life once damage has been identified. Such predictions will necessarily be probabilistic in nature and will utilize the tools of reliability analysis.

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STOCHASTIC EVALUATION OF BRIDGE CONTROL WITH SIDE WINGS

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The use of separated control surfaces attached beneath the deck of long-span bridges as a method for controlling wind induced vibrations, namely, buffeting and fluttering, is analyzed from a stochastic point of view. To this end the a state space formulation of the controlled bridge is used. This formulation was analyzed varying the different parameters involved in the structural control. Both self-excited and buffeting forces are considered. The structural control strategy applied is the LQG both in the open-and closed-loop forms. The stability of the models are analyzed under the deterministic as well as the stochastic points of view. In the first case the wind disturbances were simulated using an autoregressive model. In the latter case, the statistical moment stability was analyzed over a state-space, parametric random vibration system of equations considering the situations described above. The paper compares different models and formulations in order to obtain a detailed picture on the effectiveness of the control wings.

STATISTICAL STRUCTURAL HEALTH MONITORING

PRELIMINARY STUDY OF A BAYESIAN PROBABILISTIC SYSTEM IDENTIFICATION APPROACH FOR STRUCTURAL HEALTH MANAGEMENT

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Two distinct thrust areas that have emerged in the field of structural health management include the development of methodologies/algorithms for detecting the damage and/or changes in the dynamic characteristics of the system, and the sensing/detection devices for capturing the required data/information. A critical and essential requirement for in-depth understanding of the nature of changes encountered in the system, and for developing “integrated” and “adaptive” systems that can “manage” and maintain the integrity of the structure, is the identification of the system model, and updating the knowledge about the changes in its dynamic characteristics. This requires that the inherent uncertainties and the probabilistics of the system and/or the environmental conditions are taken into account. It has been in response to this need that the probabilistic/statistical structural health monitoring has emerged as an active research area. The Bayesian probabilistic system identification approach is one such approach. This approach allows to continuously optimize the “posterior” probably density function (pdf) by adapting the predefined “priori” pdf based on “new” measurements. The optimal pdf function is then used for estimating both the system parameters and their associated uncertainties. The accuracy of the estimation is important for structural damage detection, in probabilistic measures, and reliability analysis. However, most of the research efforts have been focused on constructing optimal numerical schemes based on simulated data.

In this paper, the Bayesian approach is applied to identify system parameters using both simulation and experimental data. A three-story shear-building prototype is used to investigate the efficiency of the proposed approach. To further explore the application of this system identification approach in structural health management, the pdf profiles of parameters for a damaged system are studied and compared with those of the corresponding healthy system. This work is part of an ongoing project sponsored by the National Institute of Aerospace and in collaboration with researchers from NASA Langley Research Center.

STATISTICAL STRUCTURAL HEALTH MONITORING

BAYESIAN INFERENCE APPLIED TO STRUCTURAL MODEL UPDATING AND DAMAGE DETECTION

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A Bayesian framework is presented for structural model selection and damage detection utilizing measured dynamic data. The framework consists of a two-level approach. At the first level the problem of estimating the free parameters of a model class given the measured data is addressed. At the second level the problem of selecting the best model class from a set of competing model classes is addressed. The application of the framework in structural damage detection problems is then illustrated. The structural damage detection is accomplished by associating each model class to a damage location pattern in the structure, indicative of the location of damage. Using the Bayesian model selection framework, the probable damage locations are ranked according to the posterior probabilities of the corresponding model classes. The severity of damage is then inferred from the posterior probability of the model parameters corresponding to the most probable model class. Computational issues are addressed related to the estimation of the optimal model within a class of models and the optimal class of models among the alternative classes. Asymptotic approximations as well as efficient Monte Carlo simulations are presented for estimating the probability integrals arising in the formulation. For illustration purposes, the methodology is applied to the identification of location and severity of damage of a chain-like spring mass structure using measured modal data. It is demonstrated that damage detection depends on the information contained in the data, the number of observed modes and the number of measured locations. In particular, prediction of location and severity of damage can be improved by optimizing the sensor configuration in the structure.

BAYESIAN ANALYSIS OF THE PHASE II IASC-ASCE STRUCTURAL HEALTH MONITORING EXPERIMENTAL BENCHMARK DATA

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A two-step probabilistic structural health monitoring approach is used to analyze the Phase II experimental benchmark studies sponsored by the IASC-ASCE Task Group on Structural Health Monitoring. This study involves damage detection and assessment of the test structure using experimental data generated by hammer impact and ambient vibrations. The two-step approach involves modal identification followed by damage assessment using the pre- and postdamage modal parameters based on the Bayesian updating methodology. An Expectation-Maximization algorithm is proposed to find the most probable values of the parameters. It is shown that the brace damage can be successfully detected and assessed from either the hammer or ambient vibration data. The connection damage is much more difficult to reliably detect and assess because the identified modal parameters are less sensitive to connection damage, allowing the modeling errors to have more influence on the results.

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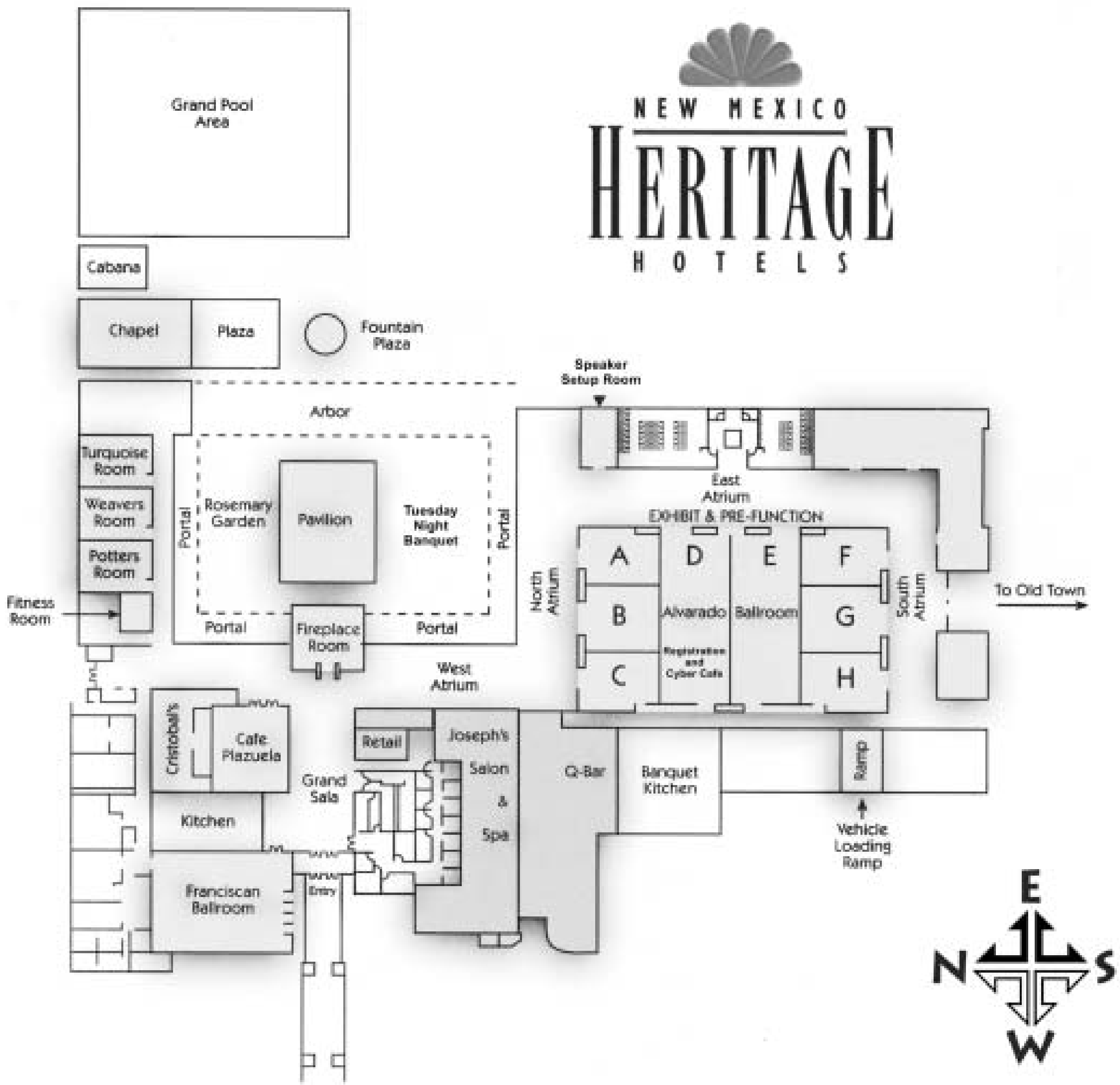

NEW MEXICO
HERITAGE
HOTELS
Grand Pool Area
Cabana
Chapel
Plaza
Fountain Plaza
Speaker Setup Room
Arbor
Turquoise Room
Weavers Room
Potters Room
Fitness Room
Portal
Rosemary Garden
Pavilion
Tuesday Night Banquet
Portal
Portal
Fireplace Room
Portal
East Atrium
EXHIBIT & PRE-FUNCTION
North Atrium
A
B
C
D
E
F
G
H
Alvarado Ballroom
Registration and Cyber Cafe
South Atrium
To Old Town
West Atrium
Cristobal's
Cafe Plazuela
Grand Sala
Retail
Joseph's Salon & Spa
Q-Bar
Banquet Kitchen
Ramp
Vehicle Loading Ramp
Kitchen
Franciscan Ballroom
Entry
E
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Monday Technical Program: 3:30 – 5:30 PM

ROOM	**Technical Session Title**
Ballroom A	Simulation & Dynamic Reliability *
Ballroom B	Epistemic Uncertainty
Ballroom C	Modeling Uncertainties in Wind Load Effects on Buildings [>]
Ballroom F	Optimization Under Uncertainty: Session 2
Ballroom G	
Ballroom H	Uncertainty and Reliability in Geomechanics: Session 3 ^
Turquoise	Structural Control, Health Monitoring, and System Identification [+]

** Sessions Organized by ASCE Probabilistic Mechanics Committee*
[>] *Sessions Organized by SEI-ASCE Safety of Buildings Committee*
^ Sessions Organized by ASCE GI RAM
[+] *Sessions Organized by ASCE Probabilistic Mechanics Committee/ASME COUP*

Technical Program: Monday, July 26: 3:30 – 5:30 PM				
Time 24 Min. Talks (* Speaker)	Room: Ballroom A **Simulation & Dynamic Reliability** Session Chairs: Beck, J., Katafygiotis, L.	Room: Ballroom B **Epistemic Uncertainty** Session Chairs: Red-Horse, J., Tempone, R.	Room: Ballroom C **Modeling Uncertainties in Wind Load Effects on Buildings** Session Chair: Diniz, S., Gurley, K.	Room: Ballroom F **Optimization Under Uncertainty** **Session 2** Session Chairs: Mahadevan, S., Giunta, A.
3:30	Reliability Estimation for Dynamical Systems Subject to Stochastic Excitation Using Subset Simulation with Splitting Ching, J.*, Au, S., Beck, J.	Distribution-Free Uncertainty Quantification Wojtkiewicz, S.*	Gust Factors Observed in Tropical Cyclones Isabel, Lili, Isidore Gabrielle and Irene During the 1999-2003 Atlantic Hurricane Seasons Masters, F.*, Aponte, L., Gurley, K., Reinhold, T.	Stochastic Parameterization of Random Shapes in Inverse Acoustic Scattering Faverjon, B.*, Ghanem, R.
3:54	Methods of Analysis for Large Nonlinear Systems Subjected to Stochastic Excitation Schuëller, G. I.*	The Notion of Independence when Probabilities are Imprecise Tucker, W., Ferson, S.*, Oberkampf, W.	Application of Standardized Data Management Protocols for Wind Loading on Low-Rise Buildings Lim, J.*, Ho, T., Morrish, D., Endo, M., Bienkiewicz, B.	Efficient Shape Optimization Technique Using Stochastic Response Surfaces and Local Sensitivities Kim, N.*, Wang, H., Queipo, N.
4:18	An Importance Sampling Procedure for Estimating Failure Probabilities of Dynamic Systems Ivanova, A., Naess, A.*	Free Vibration of Structures with Interval Uncertainty Modares, M.*, Mullen, R.	Building Orientation and Wind Effects Estimation Hanzlik, P., Diniz, S.*, Grazini, A., Simiu, E.	An Efficient Methodology for the Optimization of Structures under Stochastic Loading Jensen, H.*
4:42	Auxiliary Domain Method for Solving Nonlinear Reliability Problems Katafygiotis, L.*, Cheung, S. H.	Efficient Calculation of CDF and Reliability Bounds Using Random Set Theory Tonon, F.*	Probabilistic Performance Criteria for Tall Buildings Subjected to Wind Diniz, S.*, Iancovici, M., Riley, M., Simiu, E.	Life-Cycle Cost Analysis Under Uncertainty Furuta, H.*, Kameda, T., Frangopol, D.
5:06	Nonlinear Finite Element Response Sensitivity Analysis of Steel-Concrete Composite Beams Barbato, M., Zona, A.*, Conte, J.	Reducing the Variation Bounds of Engineering Failure Risk Predictions: A Perspective on Modeling Uncertainty Problem Ghiocel, D. M.*	A Probabilistic Model of Damage to Residential Structures from Hurricane Winds Cope, A., Pinelli, J., Gurley, K.*, Murphree, J., Simiu, E., Gulatis, S., Hamid, S.	Employing Sensitivity Derivatives for Robust Optimization Under Uncertainty in CFD Putko, M.*, Newman, P., Taylor, A.

Technical Program: Monday, July 26: 3:30 – 5:30 PM				
Time 24 Min. Talks (* Speaker)	Room: Ballroom G	Room: Ballroom H **Uncertainty and Reliability in Geomechanics** **Session 3** Session Chairs: Phoon, K., Rechenmacher, A.	Room: Turquoise **Structural Control, Health Monitoring, and System Identification** Session Chairs: Buckner, G., Saadat, S.	
3:30		Probabilistic Modeling of Landslide Reactivation by Embankment Load Bourdeau, P. L.*	LMI Model Reduction for Modeling and Control of Structures Lee, Y., Johnson, E. A.*	
3:54		Reliability Theory in Slope Stability Analysis Rahhal, M. E.*, Sherfane, J., Rached, Z.	Theoretical and Experimental Investigations of Damage Assessment of Beams Vo, P. H.*, Haldar, A.	
4:18		Reliability Models for Bridge Substructures Szwed, A., Nowak, A. S.*, Withiam, J. L.	Improvements in Structural Parameter Identification for SHM Using VSDDS Elmasry, M. I.*, Au, A., Johnson, E. A.	
4:42		Tower Structures on Liquefiable Soil Excited by Random Seismic Input Popescu, R.*, Chakrabortty, P.	Defect Detection at Local Level Using Sub-Structure Model with Unknown Input Excitation Katkhuda, H.*, Haldar, A.	
5:06			Defect Identification and Structural Health Assessment Technique - Experimental Verification Flores, R.*, Haldar, A.	

RELIABILITY ESTIMATION FOR DYNAMICAL SYSTEMS SUBJECT TO STOCHASTIC EXCITATION USING SUBSET SIMULATION WITH SPLITTING

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A new Subset Simulation approach is proposed in this paper for reliability estimation for dynamical systems subject to stochastic excitation. The basic idea of Subset Simulation is to consider a small failure probability as a product of larger failure probabilities conditional on intermediate failure events. This new approach does not require Markov Chain Monte Carlo simulation, in contrast to the original method, to generate conditional samples for estimating the conditional probabilities; instead, only direct Monte Carlo simulation is needed. The method employs splitting of a trajectory that reaches an intermediate failure level into multiple trajectories subsequent to its first passage time. This exploits an important feature of causal dynamical systems, namely, the distribution of the future excitation subsequent to the first passage time and conditional on the previous excitation is just equal to its unconditional counterpart. The statistical properties of the failure probability estimates are presented, where it is shown that the estimates are unbiased and formulas are derived to assess the error of estimation, including the coefficient of variation of the estimates. The resulting algorithm is simple and easy to implement. Two examples are presented to demonstrate the effectiveness of the new approach, also to compare with the original Subset Simulation and with direct Monte Carlo simulation.

SIMULATION & DYNAMIC RELIABILITY

METHODS OF ANALYSIS FOR LARGE NONLINEAR SYSTEMS SUBJECTED TO STOCHASTIC EXCITATION

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In this presentation, various methods capable to analyze larger structural systems with nonlinearities will be discussed. In earlier studies (see e.g. [1]) it has been shown that, so far, only so called weight controlled simulation procedures allowed the calculation of reliability estimates of medium size structures, i.e. within an acceptable computational effort. Equivalent linearization (EQL) procedures are also capable of treating larger nonlinearities and also structures of larger dimension, but yet provide estimates of second moments only.

Just recently, the methodology was extended to quite large structural systems including nonlinearities, i.e. by using the so called Karhunen-Loéve expansion. This procedure allows the reduction of the dimension of the problem. The nonlinearities are treated by local EQL-procedures. Yet, also only 2nd moment characteristics can be obtained by these methods.

The currently available methods for analyzing larger systems with nonlinearities are compared in view of their range of validity (w.r.t. nonlinearities), capabilities of treating a particular dimensionality, the required computational efforts, the types of computational procedures used, the type of results, e.g. 2nd moments or reliability estimates, etc.

The presentation closes with an outlook on future developments.

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AN IMPORTANCE SAMPLING PROCEDURE FOR ESTIMATING FAILURE PROBABILITIES OF DYNAMIC SYSTEMS

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An iterative method for estimating the failure probability for time-dependent problems has been developed. On the first iteration a simple control function has been built using design point weighting principles for serial reliability problem. After time discretization two points were chosen to construct the compound deterministic control function. In other words it is based on the time point when the first maximum of the homogenous solution has occurred and on the point at the end of considered time interval. An importance sampling technique is used in order to estimate the failure probability functional on a set of initial values of state space variables and time. On the second iteration the concept of optimal control function developed by Milstein can be implemented in order to construct a Markov control which allows the better accuracy in the failure probability measure by a Girsanov transformation was utilized. By this procedure the CPU time was substantially reduced compared to the crude Monte Carlo procedure.

SIMULATION & DYNAMIC RELIABILITY

AUXILIARY DOMAIN METHOD FOR SOLVING NONLINEAR RELIABILITY PROBLEMS

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A novel methodology allowing for a very efficient solution of nonlinear reliability problems is presented. The target nonlinear failure domain is first populated by samples generated with the help of a Markov Chain. Based on these samples an auxiliary linear failure domain, corresponding to an auxiliary linear reliability problem, is introduced. The selection of the auxiliary domain is such that there is significant overlap between the target nonlinear failure domain and the selected auxiliary linear failure domain. Once the auxiliary domain is established the method proceeds with a modified subset simulation procedure where the first step involves the direct simulation of samples in the auxiliary linear failure domain, rather than standard Monte Carlo simulation as in standard subset simulation. It is shown that the proposed methodology is very efficient and offers significant improvements over standard subset simulation, especially when one deals with low probability failure events. The superior accuracy and efficiency of the method is demonstrated through numerical examples involving dynamic reliability problems with a very large number of random variables.

NONLINEAR FINITE ELEMENT RESPONSE SENSITIVITY ANALYSIS OF STEEL-CONCRETE COMPOSITE BEAMS

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The last decade has seen significant interest in finite element modelling and analysis of steel-concrete composite structures [1]. The behavior of composite beams, made of two components coupled through shear connectors to form an interacting unit, is significantly influenced by the type of connection between the two parts. Flexible shear connectors enable development of partial composite action [2]. In order to capture the effects of this partial composite action, the structural model must include the interlayer slip between the steel and concrete components. Compared to common monolithic beams, composite beams with deformable shear connection present additional difficulties in their nonlinear range of behavior, such as complex spatial distributions of the interface slip and force [3]. In spite of these difficulties, locking-free displacement-based elements with internal node(s) provide accurate global and local response predictions given that the structure is properly discretized [3-4].

The last few years have also seen a growing research interest in sensitivity analysis of structural response. This increasing interest is motivated by the fact that finite element response sensitivities represent an essential ingredient for gradient-based computational optimization methods that are needed for example in structural optimization, structural reliability analysis, and finite element model updating. In addition, finite element response sensitivities are invaluable for gaining qualitative and quantitative insight into the effect and relative importance of various geometric, material, and loading parameters defining the structure and its loading environment.

This paper focuses on materially-nonlinear-only static response sensitivity analysis using displacement-based finite elements for steel-concrete composite beams with deformable shear connection [3]. Realistic uniaxial constitutive laws are adopted for the concrete and steel materials and for the shear connectors. The algorithms developed for finite element response sensitivity analysis are applied to a non-symmetric two-span composite beam structure for which experimental results are available for monotonic loading condition. First, the finite element response prediction is validated by the experimental results. Then, response sensitivity analysis is performed according to the Direct Differentiation Method (DDM) and validated through Forward Finite Difference (FFD) analysis [5-6]. Selected results of response sensitivity analysis are presented in order to quantify the effect and relative importance of concrete, steel, and shear connection material parameters in regards to the nonlinear static monotonic response of the selected steel-concrete composite beam benchmark.

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DISTRIBUTION-FREE UNCERTAINTY QUANTIFICATION

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The approach to be discussed is an extension of classical interval analysis, *i.e.* "Given bounds on the input parameters to a simulation code, what is the possible extent of the range of output function?" Since the computational models of interest are black boxes, only those interval techniques that are not intrusive to the analysis code. The interval analysis problem is especially difficult in the case of black boxes as the minimum and maximum of the output(s) often occur at interior points of the ranges of the input variables, e.g. resonance phenomena. The propagation of the uncertainty in the case of interval uncertain input variables is accomplished by the formulation and solution of two global optimization problems with bounded constraints. It can be shown that this formulation is also applicable if there is enough information to specify some input parameters as random variables and others as intervals or a combination of these. Along with bounds on the outputs, a probability estimate that the output lies in this pertinent region, *e.g.* an interval or hyper-box, is calculated using Frechet bounds. It can be shown that these probability estimates are lower bounds, thus always conservative in nature

In this paper, this robustness approach will be combined with a recently developed ensemble uncertainty quantification method that allows for rapid re-analysis, *i.e.* function evaluations during the optimization problems. The method will be demonstrated in the enveloping of the frequency response function of a moderately sized structural dynamics problem.

THE NOTION OF INDEPENDENCE WHEN PROBABILITIES ARE IMPRECISE

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In probability theory, there are several ways to define the concept of independence between random variables. For instance, independence implies, and is implied by, the joint distribution (or density function) being equal to the product of the marginal distributions (or densities). Likewise, independence implies that knowing something about one variable tells you nothing about the other variable. Conversely, this mutual irrelevance of information also implies independence. Another definition involves the Fourier transform of the joint distribution being the product of the Fourier transforms of the marginals. There are, in fact, several possible definitions of independence, but, because each definition implies all the others, these concepts are all equivalent. In probability theory, the concept of independence simultaneously embodies all of these possible definitions.

However, as Couso et al. [1] pointed out, when probabilities are *imprecise* [3], these various definitions of independence between random variables are no longer equivalent. In particular, in Dempster-Shafer evidence theory, random sets theory, and probability bounds analysis, the case of independence disintegrates into several distinct concepts of independence induced by the different possible definitions. We give several numerical examples that illustrate how mathematical expressions involving uncertain numbers (i.e., Dempster-Shafer structures, random sets, and probability boxes) can quantitatively depend on how the notion of independence is conceptualized [2]. The magnitude of the quantitative differences can in some cases be remarkably large.

We also explore the conjecture that the most important concepts of independence are nested in a way that allows analysts to make conservative calculations in a convenient way. In particular, *random-set independence* appears to yield the widest uncertainty of any of the reasonable generalizations of independence. It turns out that this notion of independence is also usually the simplest to implement in numerical calculations involving imprecise probabilities. We illustrate this fortuitous situation with numerical examples and explain why it should be generally applicable to the risk assessment problems that arise in engineering applications.

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EPISTEMIC UNCERTAINTY

FREE VIBRATION OF STRUCTURES WITH INTERVAL UNCERTAINTY

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Dynamic analysis of a structural system with parameter uncertainty is presented. An interval (set-theoretic) formulation is used to represent the uncertainty in the structure's parameters such as material characteristics. Independent variations for each element are considered. Using the developed interval finite element method, it is proven that, in the presence of any physically allowable uncertainty in the structural stiffness, calculating the exact bounds on system response does not require a combinatorial solution procedure. In fact, the solutions to two deterministic problems are sufficient to bound the system frequencies. Several examples that illustrate the developed algorithm with comparisons to previous interval eigenvalue solutions are presented. The solutions show no overestimation in the bounds of the calculated frequencies which has been a difficulty with other interval procedures.

EFFICIENT CALCULATION OF CDF AND RELIABILITY BOUNDS USING RANDOM SET THEORY

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Based on Random Set Theory, procedures are presented for bracketing the results of Monte Carlo simulations in two notable cases: (i) the calculation of the entire distribution of the dependent variable; (ii) the calculation of the CDF of a particular value of the dependent variable (e.g. reliability analyses). The presented procedures are not intrusive, i.e. they can be equally applied when the function is a complex computer model (black box). Also, the proposed procedures can handle probabilistic, interval-valued, set-valued, and random-set-valued input information, as well as any combination thereof.

The calculated bounds on the CDF of the dependent variable guarantee 100% confidence, and allow for a guaranteed evaluation of the error involved in the calculations. These bounds are often enough to make decisions, and require a minimal amount of function evaluations.

An example shows that, compared to Monte Carlo simulations, the number of function calls is reduced by orders of magnitude.

REDUCING THE VARIATION BOUNDS OF ENGINEERING FAILURE RISK PREDICTIONS: A PERSPECTIVE ON MODELING UNCERTAINTY PROBLEM

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The paper illustrates how stochastic network-based, Bayesian inference and dynamic Monte Carlo techniques can be intelligently combined to develop an advanced integrated probabilistic design approach for predicting the structural failure risks within confidence-based variation bounds due to modeling uncertainty. The proposed approach that addresses engineering risk predictions uses the entire information available in the joint data-model-expert knowledge space including <u>data space information</u>, referring to inputs, material, loading, boundary condition data, or computational analysis and testing result data, but also <u>model space information</u> referring to model prediction accuracy for single or multiple physics-based design models developed for nominal and off-nominal design situations, and <u>expert-opinion space information</u> referring to engineering experience-based judgments.

The proposed stochastic approach includes all key categories of modeling uncertainties that are associated with: (i) lack of sufficient collection of data (small sample size issue), (ii) non-representative collection of statistical data wrt to the entire statistical population characteristics or stochastic system physical behavior (non-representative data issue), (iii) lack of fitting of the stochastic model wrt to a given statistical dataset, i.e. a bias is typically introduced due to smoothing (model statistical-fitting issue) and (iv) lack of accuracy of the deterministic prediction model wrt to real system physical behavior for given input data points, i.e. a bias is introduced at each predicted data point due to prediction inaccuracy (model lack-of-accuracy issue). The proposed approach can accommodate the use of multiple predictive models; for example, different physics-based models with different prediction accuracies used for nominal design conditions and offnominal conditions, respectively. Uncertain confidence-based weights based on expert judgment can be associated with these models.

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GUST FACTORS OBSERVED IN TROPICAL CYCLONES ISABEL, LILI, ISIDORE GABRIELLE AND IRENE DURING THE 1999-2003 ATLANTIC HURRICANE SEASONS

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The Florida Coastal Monitoring Program (FCMP) is one of several research programs in the U.S. that deploy portable instrumented towers in the path of landfalling hurricanes to collect high resolution wind data. The goal of the project is the characterization of overland turbulent wind behavior by quantifying the statistical descriptions of interest to structural designers. In particular, this data will provide wind tunnel modelers with turbulence information to validate that the model flow field is similar to actual conditions in a tropical cyclone. Knowledge of these descriptors has accumulated since the late 1800s, although most were derived empirically from data sets collected from thunder- and winter-storms. Whether the turbulent behavior of tropical storms and hurricanes differ from these models remains an active subject of debate

During 1999-2003, the FCMP has collected hundreds of hours of full-scale tropical cyclone wind field data using up to four instrumented towers deployed in ten different storms. This paper provides an overview of the data collection project, discusses the data reduction procedure, presents analysis of gust factors based on 10-minute and 1-hour mean wind speeds and compares the observed data to models used in structural design.

APPILICATION OF STANDARDIZED DATA MANAGEMENT PROTOCOLS FOR WIND LOADING ON LOW-RISE BUILDINGS

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A concept for database-assisted analyses of buildings and structures has been recently proposed for windresistant design of low-rise buildings [1]. One of the crucial steps to this effort is the development of a database of wind forces/pressures, for a representative set of typical geometries and terrain conditions. To date, a number of wind engineering laboratories have been involved in this task [2&3]. Point pressures on external surfaces of the building models, and in some cases internal pressures, were acquired during wind tunnel tests using electronically scanned pressure measurement systems (ESP). Nearly simultaneously sampled time series of the pressures were acquired at a number of locations (channels) ranging from approximately 100 through 900. The number of the pressure channels considered by a given laboratory depends on the capability of the available ESP system. In addition to this variability, experimental configurations vary from laboratory to laboratory. In order to ensure high fidelity of the composite database comprised of contributions from these and other laboratories, protocols for data archiving and maintenance preserving the above and other pertinent information have been proposed. This paper presents a progress report on the development of the database and
implementation of the data archiving and management protocols. The structure of the files (HDF format) used to archive specific data records and the associated pertinent information is described. Schemes proposed for the database remote and on-site management system with customized interfaces for the database contributors and users are discussed. A potential for application of higher-level data management protocols (e.g. XML) is addressed.

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BUILDING ORIENTATION AND WIND EFFECTS ESTIMATION

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The methodology for estimating wind effects presented in this paper is based on the database-assisted design approach [1]. It accounts for the effects of wind directionality, for the effects of the uncertainties in the parameters that determine wind effects, and for the effects of building orientation. The methodology yields estimates of wind effects that are far more realistic than those based on the conventional building code approach for calculating wind effects, which disregards uncertainties in those parameters, as well as the effects of wind directionality and building orientation, or accounts for these effects through the use of a blanket reduction factor. The pilot software on which the calculations presented in this paper are based is a first step toward modern, computer-intensive electronic standards wherein wind loads can be calculated by using databaseassisted, reliability-based calculations of wind effects [2, 3]. We believe such standards will go a long way toward achieving significantly safer and more economical buildings in regions affected by strong winds.

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MODELING UNCERTAINTIES IN WIND LOAD EFFECTS ON BUILDINGS

PROBABILISTIC PERFORMANCE CRITERIA FOR TALL BUILDINGS SUBJECTED TO WIND

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Database-assisted design (DAD) for wind loads consists of (1) using simultaneous measurements of wind-induced pressure time histories at a large number of taps on a model structure.s envelope, and (2) using those time histories to estimate the structural response in each member, both for rigid [1] and flexible buildings [2]. DAD allows the development of reliability procedures to estimate probabilities that the structure will satisfy specified performance criteria under extreme winds [3].

In this paper we review relevant material from [2] and outline such a procedure for tall, flexible buildings. It is shown that additional progress can be made by replacing the wind load factors specified in the ASCE 7 Standard [4] by load factors accounting in a more site- and structure-specific manner for the uncertainties inherent in the estimation of the wind effects. The internal forces and their combinations, as they appear in design interaction formulas, are affected by climatological, micrometeorological, aerodynamic, and mechanical parameter uncertainties. Research into the development of such factors would eventually result in even more reliable designs of tall buildings.

The approach used for developing appropriate load factors is an extension of the approach used for low-rise buildings in [3, 5]. In addition to the uncertainties relevant to the low-rise building case, the extended approach must take into account the uncertainties in the estimation of the natural frequencies of vibration, the modal shapes, and the damping coefficients. This extension is currently under development at NIST. The probabilistic performance criteria proposed herein account for those uncertainties and integrate information on the directional wind climate and the buildings directional aerodynamics.

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A PROBABILISTIC MODEL OF DAMAGE TO RESIDENTIAL STRUCTURES FROM HURRICANE WINDS

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The focus of this paper is the development of a practical probabilistic model for the projection of annualized insurable losses to residential structures due to hurricane damage by zip code in the state of Florida. Over half of the hurricane-related damage in the United States to date has occurred in the state of Florida, which has $1.5 trillion in existing structures currently exposed to potential hurricane devastation. It is therefore critical for the state of Florida to be able to estimate future expected insurable losses due to hurricanes and their measure of dispersion. The Florida Department of Insurance (FDOI) contracted a group of researchers to develop a public hurricane loss projection model that is fully transparent.

Most published studies use post-disaster investigations or available claims data to develop vulnerability curves based on regression techniques. This approach is highly dependent on the type of construction common to the areas represented in the data, thus limiting the predictive capabilities to similar regions of impact. In the approach adopted in the current study, the estimation of building damage induced by a windstorm is accomplished through the development of damage matrices. That is, matrices whose entries are probabilities that, within a specified range of wind speeds, a building will experience damage of various types. The wind field and the structural system are decomposed into a set of discrete wind speed ranges and several basic damage states for a given structural classification. A damage matrix is developed for each building classification that has a statistically significant presence in the state of Florida. The probabilities that occupy the cells in the damage matrix are calculated from probabilistic capacities of the basic damage states, which are gleaned from laboratory studies, post damage surveys and manufacturer ratings. Dependence between basic damage states is determined by engineering analysis of load paths. A Monte Carlo simulation methodology is employed to compare probabilistic capacity information with deterministic wind loads as imparted by an assigned peak 3-second gust.

The paper will first discuss the results of a statistically detailed county-by-county assessment of residential structural classifications in Florida. The probabilistic structural model is then detailed, and the results of Monte Carlo simulations are presented. Finally, the use of damage matrices for the estimation of annual repair/replacement costs is outlined. An example is presented to demonstrate the method.

STOCHASTIC PARAMETERIZATION OF RANDOM SHAPES IN INVERSE ACOUSTIC SCATTERING

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This paper deals with a stochastic approach for solving inverse problems in acoustic scattering while accounting for many of the associated uncertainties. This approach can be very useful in the analysis of underwater acoustic scattering data and the associated inverse problem aimed at characterizing and detecting obstacles. We then propose to solve the reconstruction of a random obstacle in an infinite medium from its scattered acoustic field. Firstly, the forward problem that consists in calculating analytically the measured scattered acoustic field is solved. Secondly, the shape of the obstacle is parameterized randomly, by using the Polynomial Chaos expansion. An objective function is then constructed that describes the statistical proximity of the predicted scattered-field from the measured one. The inverse problem is then solved for the coefficients in the stochastic parameterization of the unknown shape. The method is demonstrated using a numerical example. The mean model of the reconstructed shape is computed along with stochastic perturbations associated with modeling and measurement noise. These perturbations are quantified through several higher order terms in the Polynomial Chaos expansion of the shape. The analysis is performed for several shapes and a parametric study relative to the stochastic model of the shape is deduced.

EFFICIENT SHAPE OPTIMIZATION TECHNIQUE USING STOCHASTIC RESPONSE SURFACES AND LOCAL SENSITIVITIES

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Uncertainty in the design parameters makes shape optimization of structural systems a computationally expensive task due to the significant number of structural analyses required by traditional methods for uncertainty propagation to performance measures.

This paper presents an efficient shape optimization technique based on stochastic response surfaces (polynomial chaos expansion) constructed using performance and local sensitivity data at heuristically selected collocation points. The cited expansion is constructed using Hermite polynomial bases for the space of square-integrable *pdfs* and provides: a closed form solution of the *pdf* of the performance, and the relative contribution of uncertainty inputs. The efficiency of the uncertainty propagation approach is critical since the response surface needs to be reconstructed at each design iteration.

The efficiency, accuracy, and convergence of the proposed method is evaluated using a reliability-based shape optimization problem. The results show that the uncertainty propagation component of the proposed approach requires orders of magnitude lower number of structural analyses than those required by Monte Carlo simulation, Latin Hypercube method, and the conventional Stochastic Response Surface method (i.e., without local sensitivity information). Results of the design optimization with and without uncertainty are also shown.

AN EFFICIENT METHODOLOGY FOR THE OPTIMIZATION OF STRUCTURES UNDER STOCHASTIC LOADING

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This work presents an e±cient method which allows to carry out reliability-based optimization of linear systems subjected to stochastic loading. Probability that design conditions are satisfied within a given time period is used as a measure of system reliability. The optimization problem is replaced by a sequence of approximate explicit sub-optimization problems which are solved in an e±cient manner. Approximation concepts are used to construct high quality approximations of the system dynamic responses. The approximations are combined with e±cient simulation methods to generate a moving reliability database during the optimization process. The reliability data is then e±ciently accessed by the optimization procedure and therefore the solution of each approximate optimization problem is obtained very e±ciently. The number of dynamic analysis required during the design process is reduced dramatically. In fact, numerical experience has shown that the number of system analysis required for convergence using the proposed approach is generally less than one percent of the total number of analysis required in the direct solution. In this manner, the proposed implementation is expected to be a useful tool for the optimization of large and complex structural systems subjected to stochastic excitation. An e±cient sensitivity analysis with respect to the optimization variables and general system parameters becomes also possible with the proposed formulation. The sensitivity is evaluated globally by considering the behavior of the design when the parameters vary within a bounded region. The analysis can identify the degree of robustness of the final design with respect to selected system parameters. This information can be used to determine whether or not system parameter uncertainties should be considered in the optimization process. The optimization results as well as the sensitivity information provide a deeper insight into the optimal design, including information for further decisions concerning additional analysis, if any. A numerical example in terms of a 10-storey reinforced concrete building under stochastic earthquake excitation exemplifies the proposed methodology.

LIFE-CYCLE COST ANALYSIS UNDER UNCERTAINTY

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Recently, the importance of structural maintenance has been widely recognized. In order to establish a rational maintenance program, it is necessary to develop a cost-effective decision-support system for the maintenance of existing infrastructures. Life-Cycle Cost (LCC) is a useful concept in reducing the overall cost and achieving an appropriate allocation of resources. In general, LCC optimization is the process that minimizes the expected total cost which includes the initial cost (involving design and construction), routine and preventive maintenance costs, inspection, repair, user and failure costs.

In this paper, a new optimization method is proposed, which can treat various uncertainties involved in the prediction of deteriorating and maintenance effects, and the estimation of LCC. This method is based upon Genetic Algorithm (GA) [1]. However, simple GA is not sufficient for solving the problem considered here. This is due to the complexity of the problem which includes various uncertainties and possesses many variables to be determined. In order to deal with the uncertainties, a new GA method is developed by combining GA computation and Monte Carlo simulation.

The maintenance problem for highway bridges is formulated as an optimization problem under uncertainties. In order to establish an optimum maintenance program, it is necessary to minimize the number of essential maintenances. For the long-term maintenance, it is important to predict the performance deteriorating. However, the prediction of this deterioration unavoidably involves several uncertainties.

The application of Monte Carlo simulation to GA requires a great deal of computation time. In order to reduce the computation time, a new method is introduced by implementing the evolution and sampling simultaneously. Since this method does not use the probabilistic concept directly, it may be easily understood by bridge inspectors and maintenance engineers. Realistic numerical examples are presented to demonstrate the applicability and efficiency of the proposed method.

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OPTIMIZATION UNDER UNCERTAINTY: SESSION 2

EMPLOYING SENSITIVITY DERIVATIVES FOR ROBUST OPTIMIZATION UNDER UNCERTAINTY IN CFD

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A robust optimization is demonstrated on a two-dimensional inviscid airfoil problem in both subsonic and transonic flow. Given uncertainties in statistically independent, random, normally distributed flow parameters (input variables), an approximate first-order statistical moment method (FOSM) is employed to represent the Computational Fluid Dynamics (CFD) code outputs as expected values with variances. These output quantities are used to form the objective function and constraints. The constraints are cast in probabilistic terms; that is, the probability that a constraint is satisfied is greater than or equal to some desired target probability. Gradient based robust optimization of this stochastic problem is accomplished through use of both first-and second-order sensitivity derivatives. For each robust optimization, the effect of increasing both input standard deviations and target probability of constraint satisfaction are demonstrated. This method provides a means for incorporating uncertainty when considering small deviations from input mean values.

PROBABILISTIC MODELING OF LANDSLIDE REACTIVATION BY EMBANKMENT LOAD

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Surface transportation corridors often must cross areas where slopes with marginal stability are present. In particular, construction of an embankment on a slope where the soil shear strength is already at residual state, as a result of an old landslide event, can reactivate the failure mechanism. In this paper, a probabilistic analysis is presented for assessing the likelihood of such reactivation mechanism and the magnitude of the new failure event, in the case of a trial embankment constructed in Salledes (France) on a slope with a pre-existing failure surface. Investigation and instrumentation of the site prior to the embankment construction provided information on soil properties, location of the pre-existing failure surface and groundwater conditions. Significant scattering of these data suggested a probabilistic approach to the analysis would be more relevant than traditional deterministic stability analysis methods. The modeling technique used in this case is derived from the method proposed earlier by Oboni and Bourdeau [1] for analyzing regressive slope failure cons idered as a Markovian process. Results obtained for the Salledes trial embankment case indicate strong consistency between computed probabilities of failure reactivation and the observed mechanism in the field. This suggests the proposed method can be help ful as a decision support instrument.

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UNCERTAINTY AND RELIABILITY IN GEOMECHANICS: SESSION 3

RELIABILITY THEORY IN SLOPE STABILITY ANALYSIS

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Traditional geotechnical engineers recognize that they deal with an uncertain world. They also worry that engineering judgment might fade away if one puts emphasis on risk analysis. Reliability analysis provides a framework for establishing appropriate factors of safety and leads to a better appreciation of the relative importance of uncertainties in different parameters. The aim of this study is to understand the effect of non uniform geotechnical properties of a slope when undertaking a stability analysis. Actually, the scatter of geotechnical properties is a major issue in risk assessment. While limit equilibrium generates a global factor of safety which interpretation sometimes does not reflect reality, the concept of reliability index $ß_{HL}$ introduces a new approach of safety. This new understanding of safety is related to failure risk estimation by a mathematical relative probability. In fact, the calculated probability allows taking into account the statistical scatter of geotechnical as well as geometrical properties of slopes. This reliability approach seems to be more realistic.

In our research, a clayey slope presenting two different soil layers is considered. The reliability method is applied and multiple mutually correlated shear strength parameters (c’, Φ’), as well as autocorrelated are studied. The effect of spatial variability of geotechnical properties is studied through autocorrelation distances (θ_x, θ_y). For example, for $p_{c\Phi}$= -0.2 and (θ_x, θ_y)= (120,6), the reliability index $ß_{HL}$ is equal to 7 compared to 5 in the absence of autocorrelation distances. On the other hand, the probability of failure increases from 10^{-10} in the presence of autocorrelation to 10^{-6} in the absence of autocorrelation. The effect of variation of the correlation coefficient between cohesion and friction on the reliability index $ß_{HL}$ is analyzed as well. Moreover, it is shown that when the coefficient of variation of random variables decreases, reliability index increases. Comparing probabilities of failure of probabilistic and deterministic calculations outlines the importance of considering uncertainties. On the other hand, variances of random variables should be eventually reduced, in order to take into account the spatial variability. Ignoring autocorrelation is conservative; but the 2 to 6 orders of magnitude conservatism in the probability of failure is probably more than desired.

The use of reliability techniques does not eliminate the need for sound geotechnical engineering judgment regarding both the data and the techniques on which the analyses are based. The concept of security has changed and is beyond deterministic calculations. Future work should consider a probabilistic approach in studying slope stability to account for risk factors.

RELIABILITY MODELS FOR BRIDGE SUBSTRUCTURES

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The paper objective is to develop a reliability analysis procedure for retaining walls and bridge abutments, and apply it to determine the relationship between the major design parameters and reliability index. The load components include dead load, vertical and horizontal earth pressure, surcharge, and live load. Three limit states are considered: bearing capacity of the soil, sliding and overturning. The most important parameter in the reliability analysis is the effective stress friction angle of the soil. The reliability indices are calculated using Monte Carlo simulations for a typical retaining wall and a typical bridge abutment. The results of the sensitivity analysis indicate that reliability index is most sensitive with regard to resistance factor and horizontal earth pressure.

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UNCERTAINTY AND RELIABILITY IN GEOMECHANICS: SESSION 3

TOWER STRUCTURES ON LIQUEFIABLE SOIL EXCITED BY RANDOM SEISMIC INPUT

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As a dynamic system, any soil deposit has its own characteristic frequency, which depends on soil properties, geometry, and degree of saturation. This characteristic frequency may decrease during dynamic excitation, due to degradation of the effective shear moduli as a result of pore pressure build-up and/or large shear strains. Any mechanical system is more sensitive to dynamic loading as its characteristic frequency becomes closer to the frequency range corresponding to the maximum spectral values of the excitation. Consequently, both the frequency content of seismic excitation and the evolution of structural frequency characteristics can make a significant difference in the dynamic response of soil-structure systems.

Tower structures, idealized as single d.o.f. systems and placed on a liquefiable soil deposit, are subjected to random seismic excitation. The acceleration time histories are digitally generated as non-stationary stochastic processes with evolutionary power, compatible with given seismic response spectra and envelopes. Nonlinear dynamic finite element analyses are performed using fully coupled solid-fluid equations and a multi-yield plasticity soil constitutive model. The calculations are performed for a range of seismic acceleration intensities and the results are presented in terms of fragility curves expressing the probability of exceeding a certain degree of damage as a function of earthquake intensity.

LMI MODEL REDUCTION FOR MODELING AND CONTROL OF STRUCTURES

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Mathematical representations of structural systems are often constructed using finite element and other approaches that result in high-fidelity but high-order models. In many applications, there are less complex models that will sufficiently characterize the dynamical behavior and that are easier to handle. For example, designing control strategies for high-dimensional systems can be problematic due to numerical difficulties in solving large systems of equations (*e.g.*, Riccati equations). Thus, model reductions methods have been developed to compute high-fidelity, low-order models. Such models always depend on the metric used to determine how close the reduced-order model is to the original, and the best model of a certain order is generally not the same with different metrics.

Some model reduction methods that are often used are modal truncation, static and dynamic condensation [1,2], and balanced truncation methods [3–5]. Each of these methods have their own special features. One common limitation of many model reduction techniques is that the topology of the structure — *i.e.*, how it is built up from various interconnected substructures — is destroyed. Recently, a method [6] has been developed to use linear matrix inequalities [7] to compute reduced-order models that allow the designer to impose and maintain a topology through the model reduction process.

This paper studies the effects on topology and the fidelity of a number of these model reduction techniques. As a testbed, the 3-, 9- and 20-story SAC structures, used previously for a nonlinear seismic building benchmark problem [8], are reduced to various model orders. The fidelity of the models are studied by examining key transfer functions, and the response to several historical earthquakes.Particular focus is on explaining the structured LMI model reduction and examining the reduced-order model it produces.

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STRUCTURAL CONTROL, HEALTH MONITORING, AND SYSTEM IDENTIFICATION

THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF DAMAGE ASSESSMENT OF BEAMS

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Theoretical and experimental study of the health assessment of beams recently completed at the University of Arizona will be presented in this paper. The method can be extended to consider frame-type structures. It is a finite-element-based time-domain system identification (SI) technique to detect changes in elemental stiffness of the uniform cross section fixed-fixed and simply supported beams. Input excitation information is not required for the identification purpose. By identifying the quantifiable changes in elemental stiffness, the locations of damage in the beam can be detected.

Initially, the optimal number of finite elements required to capture the dynamic behavior of a beam was studied. The SI method was then verified using computer generated theoretical response information. Experimental investigation was then carried out to verify the algorithm. Only acceleration time histories are measured and the corresponding velocity and displacement time histories are obtained by successively integrating the acceleration record. Raw data obtained from the experiments failed to identify the elemental stiffness of the beam. Several post-processing techniques were used to remove many undesirable features from the records, including noise, high frequency, slope and DC bias. The algorithm failed to identify elemental stiffness of the beam even after the post-processing of the response data. Reasons behind the failure were then investigated. Errors in the amplitude and phase shifts were found to be the most critical. Additional mitigation methods were then proposed to reduce the amplitude and phase shift errors that enabled the algorithm successfully quantified changes in elemental stiffness. Issues related to measuring rotational accelerations in time domain are also comprehensively addressed and will be reported in the paper.

Defects, in terms of notches, were then introduced in the beam. The algorithm correctly identified the location of the defects in the beam. The details of the experimental study will be presented in this paper.

Keywords
Defect detection in a beam, time domain system identification, post-processing of data.

IMPROVEMENTS IN STRUCTURAL PARAMETER IDENTIFICATION FOR SHM USING VSDDS

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Accurate diagnosis of structural health is a vital step in protecting structures; for example, approximately 25% of U.S. bridges are rated as deficient and will require significant expenditures to rebuild/replace them (FHWA, 2002). The poor condition of some structures may be attributed to late or imprecise detection of damage. The process of monitoring structural health and identifying damage severity and location in continuous time action is generally termed structural health monitoring (SHM). Despite the need for SHM, there are many constraints that challenge the effectiveness of SHM methodologies for civil structures [1]; for example, limiting excitation to ambient sources is less expensive but limits accuracy.

The authors have recently proposed using "smart" controllable passive devices — variable stiffness and damping devices (VSDDs) — in structures to improve damage detection accuracy compared to conventional passive structures [2]. VSDDS are low-power and fail-safe devices that can provide near optimal structural control strategies for vibration mitigation [3,4] as well as provide parametric changes to increase global vibration measurement sensitivity for SHM. VSDD behaviors, such as variable stiffness mode and variable damping mode, were studied in the context of a parametric frequency domain analysis to match measured and theoretical transfer functions for a structural model using simulated experimental frequency response measurements [2].

This paper reviews the motivation and the approach for using VSDDs to improve SHM, and describes an application of these methods in the laboratory. A small-scale shaking table is used to induce motion in a two story experimental structure that acts as a two degree-of-freedom (2DOF) shear building. The structure is mounted rigidly to the top of the shake table. Some weak pretensioned springs of known stiffness are added as diagonal braces in both stories so that damage can be simulated by removing these weak springs. Further, some strong springs are used as additional diagonal bracing in one floor to simulate the effects of adding a variable stiffness element with a particular stiffness level. Several of these strong springs are added for different VSDD stiffness levels. The shake table is commanded to generate simlated ambient ground motion, first using bandlimited white noise, and later a filtered white noise that reflects local ground dynamics. The simulated VSDDs are successful in improving the damage identification in structures. It is shown that using VSDDs in identification gives parameter estimates that have better means, and smaller variations than the conventional structure approach.

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STRUCTURAL CONTROL, HEALTH MONITORING, AND SYSTEM IDENTIFICATION

DEFECT DETECTION AT LOCAL LEVEL USING SUB-STRUCTURE MODEL WITH UNKNOWN INPUT EXCITATION

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Defect state evaluation of existing structures just after natural disasters (damaging earthquakes or high wind) or man-made events (impact or blast) is a major challenge to the profession. The currently available nondestructive testing techniques are not efficient or mature enough to identify defects in existing real structures if the locations are unknown. Solution of inverse problems using system identification techniques can be used for this purpose and will be proposed in this paper.

The authors are in the process of developing a novel system identification technique that can be used for the defect identification at the element level using only limited information on noise-laden responses and without knowing the input excitation force. The proposed method is a time domain system identification technique where the structures are represented by finite element models. Only acceleration time histories recorded at node points for few seconds are needed to identify defects. It estimates the dynamic properties of the structure in terms of stiffness and damping at the local element level. The structure can be excited by any types of force including harmonic, blast, white noise, and seismic load.

The proposed algorithm will be verified with the help of several numerical examples. Theoretical responses obtained by commercially available computer program will be used for the identification purpose. Noise will be added to the theoretical responses. For verification purposes, both noise-free and noise-contaminated output response measurements will be considered. The results will show that the proposed algorithm has the ability to identify the defects in the sub-structure whether the defects are small or relatively large, and the error in the identification is considerably smaller than that of other available methods where input excitation information is used to identify a structure.

Keywords
Health assessment, defect detection, finite element and sub-structuring.

DEFECT IDENTIFICATION AND STRUCTURAL HEALTH ASSESSMENT TECHNIQUE – EXPERIMENTAL VERIFICATION

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A novel system identification technique that can defect defects at the element level and can be used for the health assessment of real structures is experimentally verified. By tracking the changes in the stiffness and damping properties of all the elements with time as the structure ages, the defect in the elements, if any, can be detected. The information can be used for in-service health assessment of real structures without disrupting normal operations.

Analytical verification of the proposed algorithm has been successfully completed. Experimental verification of the method will be presented in this paper. Steel structures will be emphasized. A three-story one bay steel frame, built in 1/3 scale to fit the experimental facility, will be considered for the study. The frame will be excited by different types of loading and acceleration time histories will be recorded at pre-selected node points. The acceleration time histories will be post-proceed to eliminate the presence of noise, high frequency, slope and DC bias. Then, the acceleration time histories will be integrated successively to obtain the velocity and displacement time histories. Using only experimentally obtained response information and completely ignoring the excitation information, the frame will be identified.

Several defects (cracks, loss of area, etc.), generally observed in steel structures, will then be introduced in the frame. The algorithm will be used to check if it can locate the defect spots. The defective element will then be replaced by the defect-free element to check if it can detect the improved behavior expected just after repair or rehabilitation. The experimentally verified algorithm then can be used for the health assessment of existing structures.

Keywords
Health assessment, system identification, finite element and signal conditioning.

Tuesday, July 27
8:30 – 9:30 AM

Plenary Lecture 2: Yannis G. Kevrekidis

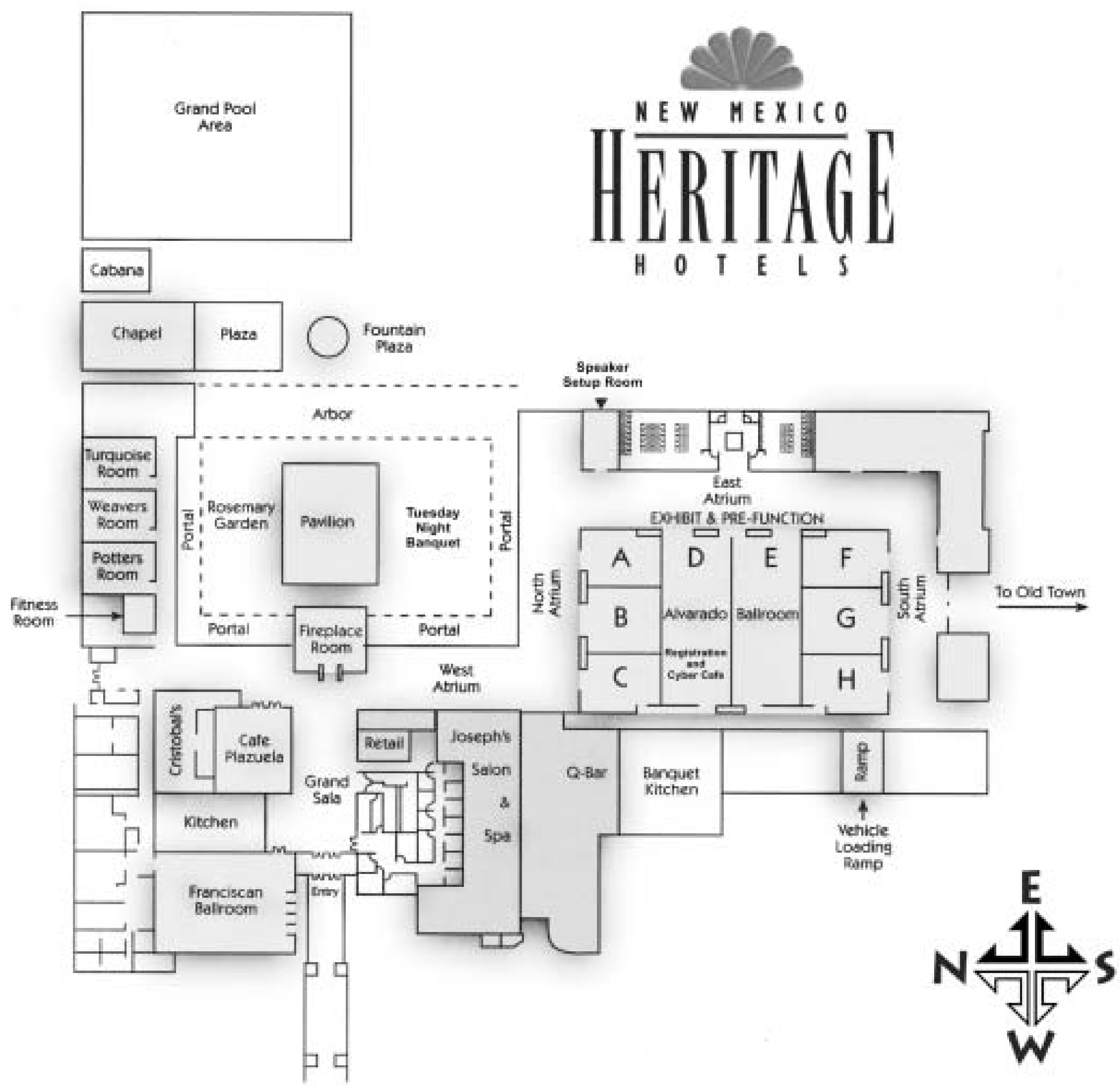
Equation-Free Modeling of Complex Systems

In current modeling, the best available descriptions of a system often come at a fine level (atomistic, stochastic, microscopic, individual-based) while the questions asked and the tasks required by the modeler (prediction, parametric analysis, optimization and control) are at a much coarser, averaged, macroscopic level. Traditional modeling approaches start by first deriving macroscopic evolution equations from the microscopic models, and then bringing our arsenal of mathematical and algorithmic tools to bear on these macroscopic descriptions.

Over the last few years, and with several collaborators, we have developed and validated a mathematically inspired, computational enabling technology that allows the modeler to perform macroscopic tasks acting on the microscopic models directly. We call this the “equation-free” approach, since it circumvents the step of obtaining accurate macroscopic descriptions.

I will argue that the backbone of this approach is the design of (computational) experiments. In traditional numerical analysis, the main code =93pings=94 a subroutine containing the model, and uses the returned information (time derivatives, function evaluations, functional derivatives) to perform computer-assisted analysis. In our approach the same main code “pings” a subroutine that sets up a short ensemble of appropriately initialized computational experiments from which the same quantities are estimated (rather than evaluated). Traditional continuum numerical algorithms can thus be viewed as protocols for experimental design (where “experiment” means a computational experiment set up and performed with a model at a different level of description).

Ultimately, what makes it all possible is the ability to initialize computational experiments at will. Short bursts of appropriately initialized computational experimentation-through matrix-free numerical analysis and systems theory tools like variance reduction and estimation- bridges microscopic simulation with macroscopic modeling. Remarkably, if enough control authority exists to initialize laboratory experiments "at will", this computational enabling technology can become a set of experimental protocols for the equation-free exploration of complex system dynamics.


NEW MEXICO
HERITAGE
HOTELS
Grand Pool Area
Cabana
Chapel
Plaza
Fountain Plaza
Speaker Setup Room
Arbor
Turquoise Room
Weavers Room
Potters Room
Fitness Room
Portal
Rosemary Garden
Pavilion
Tuesday Night Banquet
Portal
Portal
Fireplace Room
Portal
East Atrium
EXHIBIT & PRE-FUNCTION
North Atrium
A
D
E
F
B
Alvarado
Ballroom
G
Registration and Cyber Cafe
C
H
South Atrium
To Old Town
West Atrium
Cristobal's
Cafe Plazuela
Retail
Joseph's
Salon
&
Spa
Q-Bar
Banquet Kitchen
Ramp
Grand Sala
Kitchen
Franciscan Ballroom
Entry
Vehicle Loading Ramp
E
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W

Tuesday Technical Program: 8:30 AM – 12:00 PM

Ballroom E	**Announcements and Plenary Session: 8:30 – 9:30 AM** Equation-Free Modeling of Complex Systems Yannis G. Kevrekidis Princeton University
	TUESDAY MORNING, JULY 27: 10:00 AM – 12:00 PM
ROOM	**Technical Session Title**
Ballroom A	Computational Stochastic Dynamics: Session 1 *
Ballroom B	Reliability of Wood Structures
Ballroom C	Reliability of Marine Structures
Ballroom F	
Ballroom G	Model Validation and Uncertainty Quantification: Session 1 *
Ballroom H	Probabilistic Material Characterization and Analysis: Session 1
Turquoise	

** Sessions Organized by ASCE Probabilistic Mechanics Committee*

Technical Program: Tuesday, July 27: 10:00 AM – 12:00 PM				
Time 24 Min. Talks (* Speaker)	Room: Ballroom A **Computational Stochastic Dynamics** **Session I** Session Chairs: Schueller, G., Papadimitriou, C.	Room: Ballroom B **Reliability of Wood Structures** Session Chairs: Ghanem, R., Sørensen, J. D.	Room: Ballroom C **Reliability of Marine Structures** Session Chairs: Zhao, Z., Ditlevsen, O.	Room: Ballroom F
10:00	Response of Dynamical Systems Through Solution of Moment Equations Using Mixtures Wojtkiewicz, S.*	Load Bearing Capacity of Timber Roof Trusses Sørensen, J. D.*, Damkilde, L., Munch-Andersen, J.	Bayesian Estimation of Parameters Using Simultaneously Monitored Processes Friis-Hansen, P.*, Ditlevsen, O.	
10:24	Time-Frequency Characterization of Nonlinear Dynamical Systems Kijewski-Correa, T.*, Kareem, A.	Simplified Application of the FEMA 351 Probabilistic Seismic Performance Evaluation Guidelines to a Woodframe Building Luco, N.*	Probabilistic Barge Impact Analysis Patev, R.*	
10:48	Implicit Modeling of the Power Spectral Density of the Response of a Class of Nonlinear Oscillators Yang, B.*, Mignolet, M.	Estimating Structural Reliability Under Hurricane Hazard: Applications to Wood Structures Rajagopalan, B.*, Ou, E., Corotis, R., Frangopol, D.	Modifying Reliability Based Design to Include Durability Post, N., Lesko, J.*, Case, S., Hess, P.	
11:12	A Conditional Path Integration Method and its Use in Nonlinear Stochastic Dynamics Naess, A.*, Mo, E.	Reliability of Low-Rise Wood Construction Against Hurricane Winds Li, Y.*, Ellingwood, B.	On-Line Nondestructive Inspection for Fatigue Reliability Assessment and Updating for Pressure Vessels Haldar, A.*, Chen, G.	
11:36	Random Vibration Analysis of Hysteretic Structures by FORM Fujimura, K.*, Der Kiureghian, A.			

Technical Program: Tuesday, July 27: 10:00 AM – 12:00 PM				
Time 24 Min. Talks (* Speaker)	Room: Ballroom G **Model Validation and Uncertainty Quantification** **Session I** Session Chairs: Huyse, L., Thacker, B.	Room: Ballroom H **Probabilistic Material Characterization and Analysis** **Session I** Session Chairs: Raphael, W., Arwade, S.	Room: Turquoise	
10:00	Accounting for Uncertain Model and Analysis Errors in Nonlinear Finite Element Reliability Analysis Bebamzadeh, A.*, Haukaas, T.	Stochastic Effects in Complex Construction Materials with Cracks Augusti, G.*, Gioffrè, M., Stazi, L., Mariano, P.		
10:24	Error Budgets and Estimation in Probabilistic Predictive Models Ghanem, R., Doostan, A.*	The Influence of Uncertainty in Crack or Slip Plane Orientations on Cracking or Localization Probabilities Brannon, R.*		
10:48	Comments on the Formulation of Polynomial Chaos Problems Walters, R. W.*	Probabilistic Study of Chloride-Induced Corrosion of Carbon Steel in Concrete Structures Lounis, Z.*, Zhang, J., Daigle, L.		
11:12	Computation of Upper and Lower Bounds in Limit Analysis Using Second-Order Cone Programming and Mesh Adaptivity Ciria, H.*, Peraire, J.	Reliability-Based Sensitivity Analysis for R/C Columns Resistance Szerszen, M. M.*, Nowak, A. S., Szwed, A.		
11:36	Multivariate Model Validation Using PCA and Similarity Factors Huang, S.*, Mahadevan, S.	Information-Based Formulation for Bayesian Updating of the Calculation of Concrete Modulus of Elasticity Raphael, W.*, Mohamed, A., Kaddah, F., Geara, F., Favre, J.		

RESPONSE OF DYNAMICAL SYSTEMS THROUGH SOLUTION OF MOMENT EQUATIONS USING MIXTURES

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Statistical moments of response are widely used in the analysis of stochastic dynamical systems of engineering interest. It is known that, if the inputs to the system are Gaussian or filtered Gaussian white noise, Ito's rule can be used to generate a system of first order linear differential equations governing the evolution of the response moments. For nonlinear systems, the moment equations form an infinite hierarchy, necessitating the application of a closure procedure to truncate the system at some finite dimension at the expense of making the moment equations nonlinear. Various methods to close these moment equations have been developed, such as equivalent linearization, Gaussian closure, maximum entropy, Hermite moment closure, central moment closure, cumulant-neglect closure, and consistent closure [1].

In this paper, the method of consistent closure introduced by Grigoriu in [1] will be followed. Specifically, a statistical mixture of Gaussian probability density functions will be used to approximate the true density function and to derive the necessary relationships needed to close the infinite hierarchy of moment equations. The method will be briefly outlined and subsquently applied to several nonlinear stochastic systems.

References

[1] M.D. Grigoriu, "A Consistent Closure Method for Non-Linear Random Vibration" International Journal of Non-Linear Mechanics, Vol. 26:857-866, 1991

COMPUTATIONAL STOCHASTIC DYNAMICS: SESSION 1

TIME-FREQUENCY CHARACTERIZATION OF NONLINEAR DYNAMICAL SYSTEMS

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The Fourier transform has revolutionized signal processing and its applications to various disciplines perhaps like no other development, permitting its users to transcend the burdens of time series analysis and view energy content in terms of harmonics. Such merits of Fourier-based analysis have led to its widespread acceptance; however, its inability to handle nonlinear and nonstationary phenomenon has proven problematic, challenging analysts to develop alternative transform techniques in the class of time-frequency analyses. Among these new transforms, the wavelet transform and Hilbert Spectral Analysis have received considerable attention, though lacking an objective comparison of their suitability for analysis of many common nonlinear and nonstationary signals. The following study engages is such a comparison for a number of classical nonlinear systems, such as the Duffing oscillator, the Lorenz Equation and the Rössler Equation to shed new light on the manner in which these two approaches characterize nonlinearities in frequency.

This work demonstrates that the two approaches provide comparable evidence of nonlinear and nonstationary features, when viewed as skeleton time-frequency plots, a presentation not commonly utilized in wavelets. However, this work also demonstrates that complete characterization of subtle nonlinearities arises through distinctly different measures: with Hilbert Spectral Analysis relying solely on instantaneous frequency while the wavelet carries more substantial evidence of subcyclic nonlinearity in its instantaneous bandwidth. An explanation of the differing representation of subcyclic and supercyclic nonlinearities by these approaches is discussed in this study. Finally, it should be emphasized that the intent of this work is not to advocate the use of one transform over the other, but rather to objectively assess their efficacy in analyzing nonlinear systems and clarify some of the misconceptions surrounding their application.

IMPLICIT MODELING OF THE POWER SPECTRAL DENSITY OF THE RESPONSE OF A CLASS OF NONLINEAR OSCILLATORS

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The determination of the power spectral density of the response of a nonlinear, deterministic oscillator subjected to a random excitation has received considerable attention, especially in the last decade. Among the particularly successful methodologies proposed is the representation of this power spectral density as that of a linear oscillator with random properties (stiffness, damping) independent of the excitation process. In most of the pertinent investigations, the probability density function of these random properties is obtained directly in terms of the characteristics of the original, nonlinear oscillator through a complex stochastic averaging based effort. A simpler approach is adopted here that is based on the selection of an appropriate parametric model for this probability density function and on the evaluation of the parameters from relevant data of the response of the original nonlinear oscillator, a strategy introduced earlier by Soize (1995).

The single well Duffing oscillator is first considered for the model development and validation. It is found that a very good to excellent matching of the power spectral densities can be achieved over the entire range of nonlinearity, from very weak to very strong, by adopting a probability density model that includes two parameters. The evaluation of these two parameters requires at least two conditions but only one readily appears, i.e. the matching of the variance of the response of the nonlinear oscillator. Two approaches are then proposed to palliate this situation, (i) enforce additional constraints, and (ii) broaden the model to include a dependence of the nonlinearity parameter.

In regards to (i) above, two particularly reliable constraints were noted that express respectively (a) the existence of an underlying amplitude process, and (b) that the mean of the random stiffness equals the value obtained by using the equivalent linearization. The inclusion of the nonlinearity parameter in the modeling of the probability density function of the random stiffness, i.e. option (ii) above, permits the use of data (e.g. the matching of the variance) at different level of nonlinearity and thereby does produce enough conditions to evaluate the unknown parameters of the model. The application of these concepts to other nonlinear oscillators is finally discussed.

COMPUTATIONAL STOCHASTIC DYNAMICS: SESSION 1

A CONDITIONAL PATH INTEGRATION METHOD AND ITS USE IN NONLINEAR STOCHASTIC DYNAMICS

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Calculating the joint probability density function of the state space variables associated with systems of nonlinear stochastic differential equations is still a heavy numerical task. Most numerical methods appear to have severe problems when faced with nonlinear systems in higher dimensions. This paper follows up previous work where applicability of the path integral method to a four-dimensional problem has been demonstrated.

Several different numerical approaches have been pursued over the years in an effort to solve these kind of problems. The most successful attempts at developing general and accurate numerical tools seem to be based on finite element (FE) techniques and path integration methods. Galerkin methods for calculating weak solutions of Fokker-Planck equations by means of orthogonal expansions have also been developed. The basic limitation of all these numerical procedures is the dimension of the problems that can be effectively solved. So far, only a few solutions have been reported for 4D problems. However, the accuracy of the obtained numerical solutions in the tail regions of the PDFs are quite uncertain.

It has been claimed that FE and PI implementations can hardly cope with dimensions higher than three. The demand on computer storage tend to rise exponentially with dimensions. However, for PI this rise can be controlled to a certain extent depending on how the numerical solution method is implemented.

In the proposed paper a new conditional path integration method for solving nonlinear stochastic differential equations (SDEs) is described. The primary goal is to construct a robust and accurate numerical solution method for solving SDEs for higher dimensional problems. At present, the solution method has been tested on a class of nonlinear oscillators subjected to coloured Gaussian noise, which is our context means the output of a second order linear filter with Gaussian white noise input. This leads to systems with 4D state spaces.

It will be demonstrated that the conditional PI method can indeed handle 4D problems with a moderate increase in CPU time compared to the 3D case, while retaining the hallmark of PI solutions: High accuracy in the tails of the PDFs.

Several numerical example studies will be presented to demonstrate the potential of the proposed method.

RANDOM VIBRATION ANALYSIS OF HYSTERETIC STRUCTURES BY FORM

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Few methods for nonlinear random vibration analysis of multi-degree-of-freedom hysteretic structures are viable for practical implementation. Until recently, the equivalent linearization method and the Monte Carlo simulation method were the only alternatives. Recently, several investigators have proposed the use of the first-order reliability method (FORM) for solution of general nonlinear random vibration problems. This method has been shown (Koo and Der Kiureghian 2003) to be more accurate than the equivalent linearization method for high-threshold problems, and more efficient than the Monte Carlo simulation method for small probability problems. In this paper, an implementation of this method in PEER's OpenSees software is described. To increase the efficiency of the algorithm for finding the design point excitation, a "warm" starting point is obtained by use of the "mirror image excitation" (Koo and Der Kiureghian, 2003) and shifting of the design point excitation from nearby time points. It is shown that this scheme provides significant saving in the number of required dynamic and sensitivity analyses. Examples to single- and multi-degree-of-freedom hysteretic structures demonstrate the application and accuracy of the method.

References

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LOAD BEARING CAPACITY OF TIMBER ROOF TRUSSES

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In structural timber elements the strength and stiffness will vary randomly along the elements due to the natural variability in timber strength. For example the bending strength can be modeled by a sequence of strong and weak cross sections with random strength and stiffness and with random length of the strong sections. In structural systems made of timber beams a systems effect can be expected due to the following two reasons.

First, it is unlikely that the maximum load effects occur at cross-sections with very low strength. Secondly, the loads in a statically indeterminate structure will tend to be carried by the stiffer parts and therefore the weakest parts will be relieved, as stiffness and strength are positive correlated. Further, there can be system effects due to non-linear material behavior. In this paper a stochastic model is established for the bending strength and stiffness of timber beams. Next, stochastic models for typical timber structural systems such as roof trusses are established and statistical characteristics of the load bearing capacity are determined. The results show a significant increase in the characteristic (nominal) value and a reduction in the coefficient of variation (COV) for typical loads such as permanent, snow and imposed loads. Finally, reliability analyses show that the material safety factors can be reduced for timber systems compared to single timber elements. The results have been implemented in the Danish code for timber structures.

SIMPLIFIED APPLICATION OF THE FEMA 351 PROBABILISTIC SEISMIC PERFORMANCE EVALUATION GUIDELINES TO A WOODFRAME BUILDING

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The FEMA 351 guidelines for seismic evaluation (and upgrade) of existing welded steel moment-frame buildings represent a major step towards practical implementations of probabilistic performance-based assessments [1]. Even so, a present-day structural engineer may find the guidelines to be rather complicated, and hence difficult to generalize. In this paper, a simplified step-by-step procedure derived from the same basis as the FEMA 351 guidelines [2] is demonstrated for a building model borrowed from the CUREE-Caltech Woodframe Project [3]. Like in FEMA 351, the performance objective considered consists of the specification of one or more performance levels (e.g., incipient damage and incipient collapse) and an acceptably low probability of exceeding each (within a specified period of time). Unlike FEMA 351, though, the level of confidence that each of these exceedance probabilities does not surpass its tolerable limit is not evaluated, and this check is not recast into a demand and resistance factor design format. Instead, the goal of the evaluation procedure outlined here is relatively transparent – i.e., to compare the mean probability of exceeding each performance level with its tolerable limit, similar to DOE 1020 [4]. Incremental Dynamic Analyses [5] of the example woodframe building provides much of the data needed to carry out the procedure.

References

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ESTIMATING STRUCTURAL RELIABILITY UNDER HURRICANE HAZARD: APPLICATIONS TO WOOD STRUCTURES

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We propose a stochastic nonparametric framework to estimate structural reliability under hurricane wind hazard. In this, scenarios of maximum sustained wind speeds are simulated using nonparametric density estimators based on the historical wind speed data. Nonparametric methods unlike parametric alternatives, is data driven and needs no prior assumption as to the form of the underlying probability density function. They are "local" methods in that estimates at any desired point is based on a small number of data points in its neighborhood and thus, have the ability to capture any arbitrary (skewed, bimodal, etc.) underlying density function that the data might exhibit. The generated wind scenarios are convoluted with fragility curves for the different types of wood structures to obtain the failure probability and consequently, the reliability. This is done for each year for an assumed life of the structure, thus, providing time varying estimates of structural reliability. It was found that the sustained wind speeds are related to large-scale climate phenomenon in the tropical Pacific Ocean, El Nino Southern Oscillation (ENSO). Therefore, the wind scenarios had to be simulated conditioned on these large-scale climate phenomenon. This is easily possible with the nonparametric methods.

We demonstrate the utility of this framework in estimating the structural reliability of different wood structures over South Florida, North Carolina and South Texas. Significant differences in structural reliability relative to the state of the large-scale climate phenomenon, especially, ENSO were observed. This underscores the need for interdisciplinary approach to structural reliability estimation.

RELIABILITY OF LOW-RISE WOOD CONSTRUCTION AGAINST HURRICANE WINDS

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The majority of residential buildings in hurricane-prone coastal areas of the United States are of wood construction. In the past decade, hurricane winds have caused enormous property damage and economic losses to residential buildings, impacting individuals, communities and the insurance industry heavily. Light-frame residential construction traditionally has been non-engineered, and there is a need for better understanding their performance against windstorms to develop an engineered approach to their design. A key issue is to how to properly consider and model inherent uncertainties (resistance and loading) and epistemic uncertainties in the probabilistic structural system analysis that must accompany any design improvements.

Research is underway to develop a framework for assessing the reliability of wood residential construction exposed to wind hazards at various performance levels, ranging from contents damage to incipient structural collapse. Reliability analyses are performed for common building configurations and construction practices in the Southeast United States. A log-normal distribution fragility model is validated and subsequently used to determine probabilistic response of common types of wood residential construction. The fragility analysis incorporates probabilistic information of wind load (gustiness, building exposure, and internal and external building pressures) and resistance (roof panel uplift, roof truss-to-wall connections, and wall anchorage). The focus is on performance of wood systems; hurricane wind speeds are modeled based on research published in the archival literature. Epistemic uncertainties due to the selection of hurricanes wind-field models and resistance statistic s based on small samples of test data are included in the reliability analysis.

BAYESIAN ESTIMATION OF PARAMETERS USING SIMULTANEOUSLY MONITORED PROCESSES

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This paper is about extending the method of maximum likelihood estimation of spectral parameters of a stationary Gaussian process as it is presented in a recent paper by the authors [1]. The extension aims at making inference from several simultaneously monitored response processes to obtain knowledge about other not monitored but important response processes when the structure is subject to some Gaussian load field in space and time. The considered example is a ship sailing with a given speed through a Gaussian wave field of unknown spectral parameters. The monitored responses may be stress processes at given points of the ship hull, acceleration processes of the ship hull at specific points, motion of the ship relative to the wave elevated sea surface monitored at other specific points, radar obtained wave data, etc. All these processes are mutually dependent due to their common cause, and they are modeled by use of the so-called strip theory load approximation. The formulated joint likelihood function of several parameters has a complicated mathematical form. However, its large sample asymptotic form is sufficiently operational for numerical analysis to allow an approximate Bayesian updating and control of the time development of the parameters. Some of these parameters can be structural parameters that by too much change in value reveal progressing damage or other malfunctioning. Thus current process monitoring and updating can be an aid for the operation of a complicated technical system (large important structure, ship, wind power engine, etc.).

In an example the heave and pitch motions of a ship sailing in an oblique sea state are simulated pretending that these motions are monitored by accelerometers mounted on the ship. The simulation is made for selected parameters defining the Gaussian sea state, the mass distribution of ship and cargo, the vessel speed, the heading angle, and the added hydrodynamic mass and damping model. These time series are used to illustrate how various parameters such as added mass, damping, heading – including their joint Bayesian distribution – can be estimated by the described maximum likelihood procedure.

Moreover a second time series is simulated with one of the model parameters altered as it might happen in connection with the occurrence of an unnoticed damage to the ship. It is illustrated how a likelihood ratio test can be used to reject the zero hypothesis of no change and thus reveal that possible progressing damage of the ship is developing.

References

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PROBABILISTIC BARGE IMPACT ANALYSIS

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This paper will present the probabilistic procedures developed to assist with the design and analysis of navigation structures for impact loads due to transiting vessels. The uncertainty in loadings due to a wide range of events from both natural and human sources are crucial in design of these critical structures. These uncertainties are defined in terms of the distributions for impact angles, velocities and tow masses as well as the need to account for loss of power and control events. The methods developed for the design and analysis of these structures are focused on defining the return periods for the usual, unusual, and extreme loads for the navigation structures. As part of this presentation the results of the full-scale barge impact experiments and the development of a new empirical model will be discussed. Examples and a demonstration of the probabilistic procedure developed will be highlighted for the design of an upper guide wall at a navigation project.

RELIABILITY OF MARINE STRUCTURES

MODIFYING RELIABILITY BASED DESIGN TO INCLUDE DURABILITY

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We present here a perspective on a design guideline developed for composite structures based on reliability and the AASHTO load resistance factor design (LRFD) approach. We develop a simulation that may assist in the determination of reduction factors, or Φ's, applied to the resistance for a FRP structure under a particular service environment. Our analysis incorporates the residual strength based life prediction approach to develop an understanding of change in resistance with service. Simulations are validated at the coupon level for pultruded E-glass/Derakane 650-900 and VARTM E-Glass/Derakane 510A40 under fatigue conditions. The approach has shown robust in predicting probability of failure when compared to experiments. The computation of reliability index is also completed and compared to those noted in AASHTO guidelines for simple applications. Expanding this approach to the component level under realistic service conditions is discussed.

ON-LINE NONDESTRUCTIVE INSPECTION FOR FATIGUE RELIABILITY ASSESSMENT AND UPDATING FOR PRESSURE VESSELS

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Fatigue reliability assessment of pressure vessels is an important challenge to the engineering profession. The challenge is present during the whole life of pressure vessels. Following the trend in other engineering disciplines, pressure vessels need to be designed satisfying a predetermined reliability level. The problem is comprehensively studied and will be reported in this paper. A fatigue reliability assessment technique will be presented first. Nondestructive Inspections are routinely used to maintain the reliability to an acceptable level during the life time of a pressure vessel. At present, information from the nondestructive inspections (NDIs) is rarely used for safety evaluation. Even if no crack is detected during an inspection, it provides valuable information that is often overlooked. Fatigue is a very slow process, and its risk management can be carried out by NDIs. The use of such technology is expected to be very beneficial for the process industry. The NDI techniques are being continuously improved. Intelligent Ultrasonic Test (IUT) devices are being used widely on worksite to detect defects in pressure vessels in operating condition. Defect detection capabilities of different types of IUT are expected to be different and the information on defect is also expected to be uncertain, i.e., the information may not be totally reliable. Thus, incorporation of uncertainty-filled information from NDIs needs to be incorporated to the basic fatigue reliability model. A reliability updating method will be presented to address the weakness in the current fatigue reliability evaluation procedure used for pressure vessels. The basic reliability method will be extended to estimate the updated reliability. Nondestructive inspections are generally conducted at a specified time interval. To facilitate the continuous fatigue reliability evaluation, an on-line intelligent NDI technology will be proposed. The methodology will be explained with the help of examples. It is expected that the fatigue reliability evaluation of pressure vessels will be significantly improved if the proposed method is used.

Keywords
Pressure vessel, fatigue reliability, intelligent ultrasonic tests, reliability updating using nondestructive inspections.

ACCOUNTING FOR UNCERTAIN MODEL AND ANALYSIS ERRORS IN NONLINEAR FINITE ELEMENT RELIABILITY ANALYSIS

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An objective in modern structural engineering is to simulate the complex behavior of real structural systems. This goal has been brought within reach by a rapid increase in computer power and radical improvement of predictive models during the past few decades. In fact, in engineering practice the finite element method is now an indispensable tool for prediction of structural response. However, it is critical that the computational models are validated by experimental testing and incorporation of observations from real-world structures. Moreover, predictions of structural performance can only be made in a probabilistic sense. Unavoidable uncertainties are present; epistemic uncertainty is present due to imprecise models and lack of data and knowledge and aleatory uncertainty is present due to natural variability in loads and material properties and geometrical imperfections.

In this paper, finite element reliability methods are utilized to address the present uncertainties. In the past, such methods have been used to characterize material, geometry and load parameters of the finite element model as uncertain. Subsequently, probabilities of exceeding user-defined structural performance thresholds are computed. Thus far, the model and analysis errors in the finite element analysis have not been explicitly accounted for. The objective of this paper is to introduce probabilistic models for this purpose. Four sources of uncertain model and analysis errors are recognized: 1) The “idealization error” due to the transformation of reality into a boundary value problem, 2) the “discretization error” due to the spatial discretization of the boundary value problem, 3) the “analysis error” due to the use of approximate time-stepping schemes and iterative algorithms to converge to equilibrium at each analysis step, and 4) uncertainty in the specification of the failure criteria.

A focus in this paper is the utilization of probabilistic models that allow incorporation of experimental results as they become available, as well as subjective information such as engineering judgment. The use of Bayesian methods is therefore explored. Error estimates from the theory of finite elements are also incorporated into the proposed methodology. The approach in this paper employ probabilistic methods to extend the research performed on verification and validation of numerical models in other fields than civil engineering, such as the aerospace industry. A distinguishing feature of this paper is the emphasis on nonlinear finite element analysis, motivated by the fact that structural failures normally occur under conditions of nonlinear response.

The probabilistic models developed in this paper are implemented in comprehensive finite element reliability software framework. Numerical examples are presented.

ERROR BUDGETS AND ESTIMATION IN PROBABILISTIC PREDICTIVE MODELS

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The paper focuses on a particular class of recent developments related to the quantification, propagation, and management of uncertainty, using a probabilistic framework. An attempt is made at presenting a formalism that facilitates the adaptive quantification of uncertainty and of its effect on mechanics-based predictions. In addition to the more traditional quest for estimating the probability of extreme events such as failure, attention is given to estimating the confidence in model predictions and to adaptive schemes for improving this confidence through model refinement (mechanis-tic and numerical) as well as data refinement. The possibility of performing such an adaptation can play a significant role in shaping performance-based design practice in science and engineering by quantifying the information, and its associated worth, required to achieve a target confidence in the predicted behavior of some contemplated design. The concept of combined stochastic-deterministic error and its estimation is introduced that permits the development of optimal numerical optimization strategies such as adaptive mesh refinement that are consistent with the level of accuracy justified by available data. Concepts are presented that can guide the simultaneous refinement of mesh and data. The uncertainty quantification, propagation and management framework to be presented is based on Hilbert space representations and projections of random functions. This permits the framework to be integrated with other Hilbert space representations used in computational mechanics and signal analysis.

COMMENTS ON THE FORMULATION OF POLYNOMIAL CHAOS PROBLEMS

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This paper describes a simplified formulation for Polynomial Chaos (PC) problems that is mathematically equivalent to the standard formulation that typically involves extensive use of summation notation. A new operator is introduced that results in a set of deterministic equations for the expansion coefficients that are remarkably similar to the original governing equations, simple to understand and easy to code. A few examples of both the original and revised formulations are given including non-linear convection, Laplace's equation, and the two-dimensional Euler equations of fluid dynamics. Results of treating various uncertainties by the Polynomial Chaos method along with comparisons to Monte Carlo calculations will also be presented.

COMPUTATION OF UPPER AND LOWER BOUNDS IN LIMIT ANALYSIS USING SECOND-ORDER CONE PROGRAMMING AND MESH ADAPTIVITY

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Limit analysis is relevant in many practical engineering areas such as the design of mechanical structures or the analysis of soil mechanics. Assuming a rigid, perfectly-plastic solid subject to a static load distribution, the problem of limit analysis consists of finding the minimum multiple of this load distribution that will cause the body to collapse. This collapse multiplier results from solving an in.nite dimensional saddle point problem, where the internal work rate is maximized over an admissible set of stresses -de.ned by a yield condition- and minimized over the linear space of kinematically admissible velocities for which the external work rate equals the unity. When strong duality is applied to this saddle point problem, the well-known convex (and equivalent) static and kinematic principles of limit analysis arise [1].

In this article, an e.cient procedure to compute strict upper and lower bounds for the exact collapse multiplier is presented, with a formulation that explicitly considers the exact convex yield condition. The approach consists of two main steps. First, the continuous problem, under the form of the static principle, is discretized twice (one per bound) by means of di.erent combinations of finite element spaces for the stresses and velocities. For each discretization, the interpolation spaces are chosen so that the attainment of an upper or a lower bound is guaranteed. The second step consists of solving the resulting discrete nonlinear optimization problems. Towards this end, they are reformulated into the canonical form of Second-order Cone Programs, which allows for the use of primal-dual interior point methods that optimally exploit the convexity and duality properties of the limit analysis model and guarantee global convergence to the optimal solutions.

To exploit the fact that collapse mechanisms are typically highly localized, a novel method for adaptive meshing is introduced based on local bound gap measures and not on heuristic estimates. The method decomposes the total bound gap as the sum of positive elemental contributions from each element in the mesh, and re.nes only those elements which are responsible for the majority of the numerical error. Finally, stand-alone computational certi.cates that allow the bounds to be veri.ed independently, without recourse to the original computer program, are also provided. This removes the uncertainty about the reliability of the results, which frequently undermines the utility of computational simulations.

The efficiency of the methodology proposed is illustrated with several applications in plane stress and plane strain, demonstrating that it can be used in complex, realistic problems as a supplement to other models.

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MODEL VALIDATION AND UNCERTAINTY QUANTIFICATION: SESSION 1

MULTIVARIATE MODEL VALIDATION USING PCA AND SIMILARITY FACTORS

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A new perspective for practical computational model validation considering multiple response quantities at a single location or single response at multiple locations, is proposed in this paper. The problem arises in model validation when different responses may give conflicting inference about the validity of the model. Both model prediction and experimental observation can be viewed as two data sets, which can be compared to make an inference about the validity of model prediction. Principal Component Analysis (PCA) is applied for this purpose in this paper.

Noise is present in both model prediction (e.g. numerical errors) and experimental observation (e.g. measurement errors). Using PCA for decomposition of the data filters the noise prior to model validation. By performing PCA on a multivariate data matrix, i.e., multiple responses, a transformed matrix is obtained in the feature space which is spanned by the principal components. The dimension of the feature space is less or much less than the dimension of the original space. The validation is preformed by the comparison of features instead of the original variables. Two similarity metrics are employed in the feature space to characterize the statistical equivalence of experimental data and model prediction: weighted average of cosine similarity, and distance similarity based on the Mahalanobis distance.

The proposed methodology is illustrated with a simple example and a practical problem from Sandia for the validation of a dynamic model in predicting the time history of the dynamic response.

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STOCHASTIC EFFECTS IN COMPLEX CONSTRUCTION MATERIALS WITH CRACKS

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Materials are called complex when their material texture (substructure) from nano- to meso-level has a prominent influence on their gross behavior. In sophisticated technological devices, complex materials are used because unusual high performances are required. For them, the material element may be pictured as a ‘system’ and, to describe it, one needs the introduction of an appropriate morphological descriptor **v** (order parameter) in addition to its place in space. In a general sense, it is required only that **v** be an element of an abstract manifold: then, each special choice of **v** characterizes the material model in the particular circumstance under examination. The order parameter represents the substructure of a material element only at a gross level. It is a coarse grained geometrical pictures of substructural events. For them, appropriate statistical analyses may be necessary due to material disorder, even if "quenched", i.e. not evolving with thermal variations. In some cases, higher order statistical moments of the distributions of the fields involved need to be used to furnish a satisfactory representation of each special case.

After some general remarks concerning the treatment of substructural randomness in complex materials, we focus our attention on quasicystals. They are metallic alloys that display diffraction patterns with icosahedral symmetry under excitation, induced by X-ray beams. From a geometrical point of view they are then quasiperiodic structures because the space cannot be filled by icosahedra only, and ‘worms’ that alter periodicity
must be included. In a certain sense quasicrystals are a three-dimensional picture of a six-dimensional periodic lattice: in essence, they are complex materials. To describe their mechanical behavior, two entities are necessary: the standard displacement field (phonon field) **u** and a microdisplacement field (phason field) **w** representing local rearrangements of atoms determining the quasiperiodic structure.

After their discovery in 1984, quasicrystals have been used for energy savings and for the production of thin films, fillers for composites, sinters.

In this paper, we shall evaluate by means of Monte-Carlo techniques the portraits of mean, coefficient of variation, skewness and kurtosis of phonon and phason fields around the tip of a crack in sample cases of Al-Pb-Mn alloy elements with cracks, considering the phonon-phason coupling coefficient as a random field over the body.

PROBABILISTIC MATERIAL CHARACTERIZATION AND ANALYSIS: SESSION 1

THE INFLUENCE OF UNCERTAINTY IN CRACK OR SLIP PLANE ORIENTATIONS ON CRACKING OR LOCALIZATION PROBABILITES

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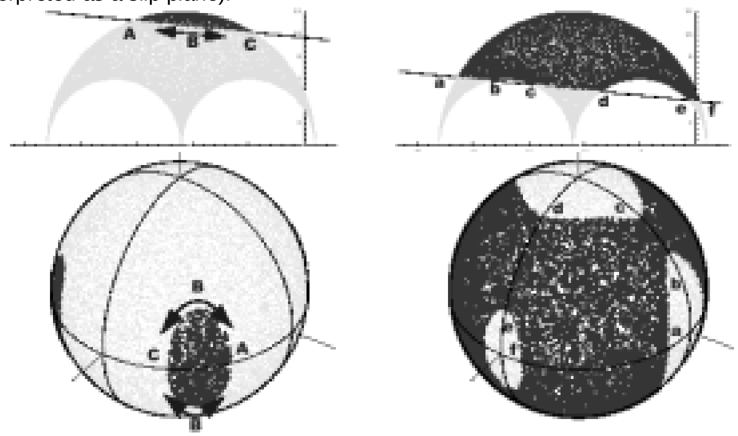
Localization (shear bands, compaction bands, fracture, etc.) cannot form in a deterministic mathematically homogenous material subjected to a homogenous stress field. Even with stress gradients, homogenous models cannot predict observed failure patterns (e.g., radial cracks in symmetric penetration). Simulations that statistically incorporate *micro*-structure variability in a *macro*scopically homogenous material can predict realistic *mesh-independent* fragment patterns. Weibull theory and similar approaches account for uncertainty in the *spatial locations* of microcracks, but relatively little work has been done to assess how flaw *orientation* influences the spread in material strength (often characterized empirically by the Weibull modulus). Mohr-Coulomb (MC) failure theory, which serves as a simple example, initiates failure when Mohr’s circle first touches the failure line, but this pre-supposes that a crack *exists* in that orientation (and a single failure line presupposes only one crack size). If not, the stress state can be intensified beyond the failure line, and the failure probability is proportional to the solid angle of unit normals that map above the failure line (see figure). By further allowing for variability in flaw sizes, realistic failure probabilities effectively transform the discrete MC failure threshold into a *fuzzy* boundary. While MC theory is used to illustrate the concepts, the basic ideas apply to *any* discrete threshold theory, or to crystal plasticity (where a crack plane is re-interpreted as a slip plane).



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PROBABILISTIC STUDY OF CHLORIDE-INDUCED CORROSION OF CARBON STEEL IN CONCRETE STRUCTURES

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The corrosion of the carbon steel reinforcement in concrete structures leads to concrete fracture, loss of bond between steel and concrete, and reduction in strength and ductility. As a result, the safety, serviceability and durability of concrete structures are reduced, while their life cycle costs are increased. Chlorides from deicing salts or seawater contaminate concrete. Corrosion of carbon steel in concrete is an electrochemical process that occurs in the concrete pore solution, in which the steel is losing its electrons at one site to react with oxygen and is oxidized at another site and is transformed into corrosion products. Normally, concrete provides the carbon steel protection from corrosion by forming a passive film, mainly insoluble ferrous or ferric oxides around the steel due to the high alkalinity of the concrete pore solution. When chloride ions reach the steel surface in the pore solution, they act as the catalyst for the corrosion reaction so that the equilibrium is disrupted. The corrosion of carbon steel will start as soon as the chloride content reaches the threshold level, which defines the resistance of carbon steel, and the rate of corrosion will increase with the chloride content. The threshold level depends on the chemistry of the pore solution, specifically the concentration of hydroxyl ions. The onset of corrosion and its rate are governed by surface chloride concentration, diffusivity of concrete, concrete cover depth of the steel, corrosion threshold level, as well as moisture level in terms of the pore solution, and the availability of oxygen. For concrete bridge deck slabs, the chloride ingress into concrete is governed by a combination of diffusion and convection mechanisms.

In this paper, the prediction of the time to onset of corrosion is based of a semi-analytical model that assumes a diffusion model for chloride transport with the use of the apparent diffusivity and surface chloride concentration. Such a model enables to take into account some of the uncertainty associated with the chloride transport model. However, given the heterogeneity of concrete and time- and space-dependence of its properties, and variability of the chemistry of the pore solution and microstructure in the same investigated structure, a probabilistic modeling of the chloride contamination of concrete and corrosion of carbon steel is proposed. The proposed model incorporates the uncertainty associated with the analytical models of chloride transport and corrosion initiation, as well as the uncertainty associated with the concrete cover depth, concrete diffusivity, surface chloride concentration, and the threshold chloride level for corrosion initiation and predicts the distributions of chloride concentration and corrosion time using Monte Carlo simulation.

The prediction capability of the proposed probabilistic model is illustrated on a case study of an aging corrosion-damaged concrete bridge deck that was exposed to chlorides from deicing salts for forty years. An extensive non-destructive and destructive evaluation of the deck was undertaken. The field survey data showed a considerable level of variability in all parameters measured with coefficients of variation ranging from 30% to 85%. The proposed probabilistic model provided very good predictions of the level of chloride contamination of the deck at different depths as well as the extent of corrosion of the reinforcing steel in the top mat.

PROBABILISTIC MATERIAL CHARACTERIZATION AND ANALYSIS: SESSION 1

RELIABILITY-BASED SENSITIVITY ANALYSIS FOR R/C COLUMNS RESISTANCE

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Paper presents the reliability analysis of RC columns subjected to eccentric load. Reliability analysis includes new load model according to ACI 318-02 “Building Code Requirements for Structural Concrete” provisions, and is based on new statistical parameters for materials (concrete and reinforcing steel). Developed closed-form sectional resistance formulas for eccentrically loaded columns are used in reliability analysis. Momentcompressive force interaction curve is described for sections depending on the mode of material failure. The proposed approach allows for creation of uniform reliability surface covering all design cases, from axial compression to pure flexure. In that way, reliability index can be expressed in terms of eccentricity of load or tensile strains in reinforcement. This approach can serve as a better basis for selection of new resistance factors for analyzed columns.

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INFORMATION-BASED FORMULATION FOR BAYESIAN UPDATING OF THE CALCULATION OF CONCRETE MODULUS OF ELASTICITY

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One of the main problems of behavior prediction procedures has always been the determination of concrete elasticity modulus. This parameter has a big importance in the evaluation of strains and particularly the ones caused by creep. In fact, its definition differs from a design code to another, and the difference between the obtained modulus can reach very large values. At first, by constituting a large database for concrete strain testing in many research European centers, a comparison is performed between the experimental results and the design codes of practice: ACI, BPEL, CEB and EUROCODE 2.

In order to improve the theoretical estimation of the modulus of elasticity, a bayesian approach is performed to correct the proposed modulus formulas in the above mentioned codes. Using the collected database, a new formulation is proposed by considering the effect of several parameters instead of the design code procedures where only one parameter (compressive strength) is considered. Therefore, the experimental results are randomly divided into two parts: one serving for model calibration while the other for verification of model robustness. The efficiency of the proposed methods have been noticed in the improvement of the elasticity modulus computation where the obtained results are largely better than classical ones.

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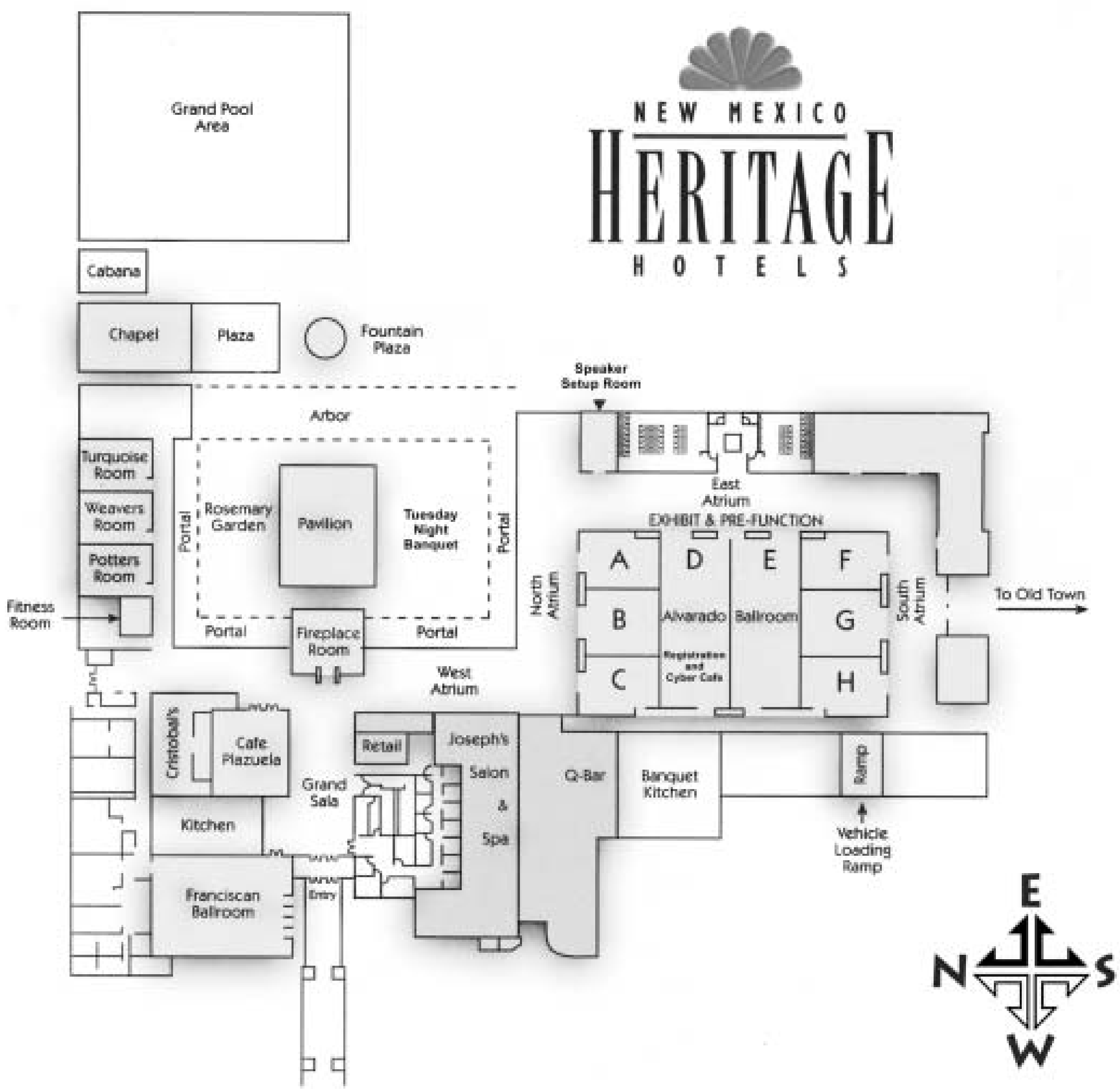
NEW MEXICO
HERITAGE
HOTELS
Grand Pool Area
Cabana
Chapel
Plaza
Fountain Plaza
Speaker Setup Room
Arbor
Turquoise Room
Weavers Room
Potters Room
Fitness Room
Portal
Rosemary Garden
Pavilion
Tuesday Night Banquet
Portal
Portal
Fireplace Room
Portal
East Atrium
EXHIBIT & PRE-FUNCTION
A
B
C
D
E
F
G
H
Alvarado
Ballroom
Registration and Cyber Cafe
North Atrium
South Atrium
To Old Town
West Atrium
Cristobal's
Cafe Plazuela
Retail
Joseph's
Salon
&
Spa
Q-Bar
Banquet Kitchen
Ramp
Vehicle Loading Ramp
Grand Sala
Kitchen
Franciscan Ballroom
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Tuesday Technical Program: 1:00 – 3:00 PM

ROOM	**Technical Session Title**
Ballroom A	Computational Stochastic Dynamics: Session 2 *
Ballroom B	Structural Reliability
Ballroom C	Earthquake Engineering: Session 1
Ballroom F	Stochastic Optimization in Engineering Design: Session 1 *
Ballroom G	Model Validation and Uncertainty Quantification: Session 2 *
Ballroom H	Probabilistic Material Characterization and Analysis: Session 2
Turquoise	Generalized Models of Uncertainty for Engineering Mechanics: Session 1 *

** Sessions Organized by ASCE Probabilistic Mechanics Committee*

Technical Program: Tuesday, July 27: 1:00 – 3:00 PM				
Time 24 Min. Talks (* Speaker)	Room: Ballroom A **Computational Stochastic Dynamics** **Session 2** Session Chairs: Schueller, G. Grigoriu, M.	Room: Ballroom B **Structural Reliability** Session Chairs: Haldar, A., Augusti, G.	Room: Ballroom C **Earthquake Engineering** **Session I** Session Chairs: Spanos, P., Deodatis, G.	Room: Ballroom F **Stochastic Optimization in Engineering Design** **Session I** Session Chairs: Royset, J., Swiler, L.
1:00	Robust Reliability-Based Optimization in Structural Dynamics Using Evolutionary Algorithms Papadimitriou, C.*, Ntotsios, E.	Solving the Multi-Dimensional Convulution Integral for System Reliability Adduri, P.*, Penmetsa, R., Grandhi, R.	Loss Exceedance Curves for a Portfolio of Structures Due to Earthquakes Deodatis, G.*, Kunreuther, H., Pressman, E., Smyth, A.	Decoupled Methodology for Probabilistic Design Optimization Agarwal, H.*, Renaud, J.
1:24	Real-Time Bayesian State Estimation of Uncertain Dynamical Systems Ching, J.*, Beck, J.	Structural-Reliability-Based Analysis of Large and/or Complex Systems Menun, C.*	Effect of Phase Spectrum Uncertainty on Earthquake Motion Sato, T.*, Murono, Y., Kawanishi, T.	Reliability-Based Optimal Design in Opensees Liang, H.*, Haukaas, T., Royset, J. O.
1:48	Simulation of Strongly Non-Gaussian Processes Using Karhunen-Loeve Expansion Phoon, K.*, Huang, H., Quek, S.	Risk-Based Condition Assessment and Maintenance Engineering for Aging Aircraft Structure Components Ghiocel, D. M. *, Wang, L.	Application of Stocahstic Characteristics of Phase Spectrum to Random Vibaration Analysis of SDOF System Murono, Y.*, Sato, T.	An rSQP Approach for a Single-Level Reliability Optimization Perez, V.*, Eldred, M., Renaud, J.
2:12	Estimation of First Excursion Probability of Nonlinear Dynamic System by Importance Sampling Technique Maruyama, O.*, Hoshiya, M.	Structural Risk Calibration Corotis, R.*	Generation of Uniform Hazard Ground Motions Using Hilbert Huang Transform Gu, P.*, Wen, Y. K.	Reliability-Based Design Optimization of Structural Systems Royset, J.*, Polak, E.
2:36	Forced Response of Composite Panels with Random Material Properties with Random Loading Singh, B.*, Yadav, D.	Reliability Analysis for Human's Comfort Laier, J.*, Venturini, W., Mohamed, A., Lemaire, M.	Macro-Spatial Correlation Structure of Seismic Ground Motions of the 1999 Chi-Chi Earthquake Takada, T.*, Shimomura, T.	Reliability-Oriented Optimization Under Combined Loading Streicher, H.*, Rackwitz, R.

Technical Program: Tuesday, July 27: 1:00 – 3:00 PM				
Time 24 Min. Talks (* Speaker)	Room: Ballroom G **Model Validation and Uncertainty Quantification** **Session 2** Session Chairs: Thacker, B., Urbina, A.	Room: Ballroom H **Probabilistic Material Characterization and Analysis** **Session 2** Session Chair: Raphael, W., Bhattacharya, B.	Room: Turquoise **Generalized Models of Uncertainty for Engineering Mechanics** **Session I** Session Chairs: Beer, M., Mullen, R.	
1:00	The Computation of Bounds for Energy Release Rates in Fracture Mecahnics Xuan, Z., Pares, N.*, Peraire, J.	Percolation Theory Approach to Quantify Geo-Material Density-Modulus Relationships Rucker, M.*	A Probabilistic Approach to Uncertainty Quantification with Limited Information Red-Horse, J.*, Benjamin, A.	
1:24	Bayesian Validation of Statistical Models Rebba, R.*, Mahadevan, S.	A Dynamical SFE Method in the Frequency Domain Falsone, G.*, Ferro, G.	Structural Reliability Application of Correlation in Random-Set Valued Variables Tonon, F.*, Pettit, C.	
1:48	Model Parameter Updating Using Bayesian Networks Treml, C.*, Ross, T.	Atomistic Simulation for Studying the Asymptotic Behavior of Ultimate Strenth of Carbon Nanotubes with Randomly Occurring Defects Bhattacharya, B.*, Lu, Q.	Time Series Analysis with Non-Precise Data – Part I Hareter, D.*	
2:12	Quantifying Total Uncertainty Using Different Mathematical Theories in a Validation Assessment Booker, J.*, Ross, T., Hemez, F., Anderson, M., Reardon, B., Joslyn, C.	Probabilistic Fatigue Life Estimation of Seeded UDIMET 720 Superalloy Specimens Ghosn, M.*, Telesman, J., Bonacuse, P., Barrie, R., Ghosn, L., Kantzos, P.	Time Series Analysis with Non-Precise Data – Part II Hareter, D.*	
2:36	Performance-Optimal and Uncertainty-Robust Decisions of the Los Alamos Project-Y Hemez, F.*	Application of Probabilistics Models for the Quantification of the Fatigue Crack Growth Ferreira, J., Andalo, J.*	Sample-Induced Simulation of Fuzzy Randomness Beer, M.*	

ROBUST RELIABILITY-BASED OPTIMIZATION IN STRUCTURAL DYNAMICS USING EVOLUTIONARY ALGORITHMS

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A methodology for the robust optimization of uncertain linear structural systems subjected to stochastic dynamic loads is presented. A reliability-based performance measure is considered which accounts for the system safety due to the stochastic load variability. Uncertainties in the system parameters are modeled as random variables with prescribed probability distributions. A robust design is defined as the one that simultaneously optimizes the mean performance and minimizes the variation of this performance to system parameter uncertainties. Thus the robust design is formulated as a multi-criteria optimization problem with the trade-off between the two criteria playing an important role in the selection of the best design. The strength Pareto evolutionary algorithm, well suited to solve multi-objective optimization problems, is used to identify a number of Pareto designs that are uniformly distributed along the Pareto front. Computational issues for estimating the mean and the variance of the structural reliability to parameter uncertainties are addressed. Approximate extreme response theories are used to obtain the reliability estimates due to the stochastic nature of the excitation. Approximations based on asymptotic expansions provide computational efficient estimates of the mean performance and its variation to parameter uncertainties. The design concepts and the effectiveness of the methodology are illustrated by applying it to the design of a tuned mass damper used for vibration control of a main structure.

REAL-TIME BAYESIAN STATE ESTIMATION OF UNCERTAIN DYNAMICAL SYSTEMS

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State estimation, the process of using dynamic data from a system to estimate quantities that give a complete description of the state of the system, has the potential to be widely applied in civil engineering. For Bayesian state-estimation algorithms, the extended Kalman filter is basically the dominant one for nonlinear systems for the last 30 years in civil engineering. However, its applicability for nonlinear systems is seldom verified either empirically or theoretically. This paper introduces recent developments in real-time Bayesian state estimation problems. In particular, a methodology based on Monte Carlo simulation is introduced and discussed in detail. It is shown that the methodology is applicable to highly nonlinear systems with non-Gaussian uncertainties and provides consistent state estimates. Recently developed techniques that are useful to improve the convergence of the Monte Carlo simulation are also introduced and discussed. Comparisons between the new methodology and the extended Kalman filter are made using several numerical examples on nonlinear systems. The results indicate that the new methodology provides consistent state estimates, while the extended Kalman filter provides inconsistent state estimates for highly nonlinear systems.

SIMULATION OF STRONGLY NON-GAUSSIAN PROCESSES USING KARHUNEN-LOEVE EXPANSION

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A random process $\varpi(x,\theta)$ indexed on a bounded domain D, having zero mean (for convenience) and finite variance, can be approximated using a finite Karhunen-Loeve (K-L) series:

$$\varpi_M(x,\theta) = \sum_{i=1}^{M} \sqrt{\lambda_i}\,\xi_i(\theta) f_i(x) \tag{1}$$

where λ_i and $f_i(x)$ are the eigenvalues and eigenfunctions of the covariance function, $\xi_i(\theta)$ is a set of uncorrelated K-L random variables with zero mean and unit variance, and M is the number of K-L terms. Phoon et al. (2002) suggested using the above expansion with non-Gaussian random variables to produce the desired non-Gaussian process. The key feature of this technique is that the target covariance function is maintained, while the probability distributions of the K-L random variables are updated iteratively:

$$\xi_i(\theta) = \frac{1}{\sqrt{\lambda_i}} \int_D \varpi_M(x,\theta) f_i(x)\,dx \tag{2}$$

The original non-Gaussian K-L procedure produces sufficiently accurate results for near-Gaussian processes, primarily because of the predominance of the first few eigenvalues. In principle, this approach is very attractive because it can be extended readily to non-stationary and multi-dimensional fields in a unified way. However, for strongly non-Gaussian cases (e.g., large skewness), the procedure is unable to match the distribution tails well. This paper proposes an effective solution to this tail mismatch problem using a modified orthogonalization algorithm that reduces the degree of shuffling within columns containing empirical realizations of the K-L random variables. Assuming n realizations of M K-L variables are stored in an $n \times M$ matrix $\boldsymbol{X}$, this modified orthogonalization can be outlined as follows:

1. Compute the product-moment covariance matrix of $\boldsymbol{X}$, say by MATLAB cov($\boldsymbol{X}$).
2. Obtain an uncorrelated realization matrix $\boldsymbol{Y}$ by:

$$\mathbf{Y} = \mathbf{X}\mathbf{Q}^{-1} \tag{3}$$

   where Q^TQ = cov(X)., say by MATLAB chol(cov(X)).
3. Re-order the realizations in each column of $\boldsymbol{X}$ to follow the ranking of realizations in each column of $\boldsymbol{Y}$.

Numerical examples demonstrate that the non-Gaussian K-L expansion produced by this modified algorithm could simulate highly skewed marginals and could potentially generate different non-Gaussian processes satisfying the same target marginal and covariance function by using different initial distribution for the K-L random variables.

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COMPUTATIONAL STOCHASTIC DYNAMICS: SESSION 2

ESTIMATION OF FIRST EXCURSION PROBABILITY OF NONLINEAR DYNAMIC SYSTEM BY IMPORTANCE SAMPLING TECHNIQUE

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In random vibration, probability of an event that system performance function becomes negative during the time duration is a means to discuss the system safety. This probability is well known as first excursion probability. Since nonlinear stochastic structural dynamics is of significant importance for reliability evaluation of earthquake, wind and ocean wave engineering problems, the development of procedures to predict structural responses has received considerable attention by engineers and consequently there are many methods proposed up to date, or being under development so far.

However, analytical solutions are available for a restricted class of systems only, whereas Monte Carlo simulation technique offers a feasible alternative for solution of first excursion probabilities except prohibitive computational costs.

This paper investigates the variance reduction technique, which is the importance sampling technique utilizing the measure transformation method for the non-linear dynamic system. To attain the purpose, the importance sampling function is obtained by using the stochastic terminal state control theory. The efficiency of the proposed method is demonstrated by numerical examples of non-linear restoring force systems under the external white noise excitation.

FORCED RESPONSE OF COMPOSITE PANELS WITH RANDOM MATERIAL PROPERTIES WITH RANDOM LOADING

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In most engineering applications, vibration is generally undesirable. The detrimental effects of vibrations on a structure are well known. An excessive vibration of the structures may even lead to its complete failure. Often, apparently harmless vibration is generally undesirable if allowed to continue over a long period, may eventually cause a fatigue failure of the structure. Such drastic failures have been observed in all kinds of structures. Hence, accurate prediction of the forced response of the structures is an important field of investigation, especially in the case of composites as the response depends on large number of parameters.

In determining the dynamic response of system made of composites, it is customary to assume that the given system has precisely defined properties. It is further assumed that the applied excitations deterministic as mentioned earlier. However, the system properties can at best be determined only within a certain range due to the large number of parameters associated with its manufacturing and fabrication processes and our inability to control them precisely. Similar is the case with loading also, which cannot be determined exactly. The uncertainties inherent in system response induced by uncertainties in system parameters and randomness in applied excitation need to be incorporated in the system modeling for a rigorous analysis. For reliability of the design, it is essential that the response should be predicted exactly. This consideration results in the need for modeling of the system properties and excitation as random. In the present work the material properties have been modeled as random variables and the excitation as a random process in time.

Considerable research has been carried out to characterize the dynamic response of the structures made of FRPs. Much of the work is based on classical random vibration theory, which focuses on the uncertainty in the response resulting from a prescribed excitation but the structural properties are assumed to be deterministic. Very little information is available on the forced vibration response of composite structures with random system parameters to deterministic as well as random loading.

In this work, a general probabilistic analysis procedure based on the state space [1] from of the system equations has been presented. These are derived using the classical and the finite element approaches for forced vibration response of composite laminated cylindrical panels with random material properties subjected to deterministic as well as random excitation. The first order perturbation technique has been chosen to handle the randomness in material properties. The formulation is based on the HSDT including rotatory inertia effects. Second order statistics of the transverse displacement of the cylindrical panels with known second order statistics of material properties and external excitation have been obtained. The results have been compared with Monte Carlo simulation technique.

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SOLVING THE MULTI-DIMENSIONAL CONVOLUTION INTEGRAL FOR SYSTEM RELIABILITY

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In probabilistic analysis, the failure probability of a structural component is estimated based on a particular performance criterion. This failure probability can be efficiently estimated by solving the convolution integral using Fast Fourier Transforms [1]. However, the failure of a structural system is governed by multiple failure criteria, all of which are to be taken into consideration for the reliability estimation. In a multidisciplinary environment, where all the failure criteria are equally important, there is no methodology to convert the system reliability problem into a component reliability problem. These failure criteria are often correlated and the accuracy of the estimated structural failure probability of the system highly depends on the ability to model the joint failure surface.

Monte Carlo simulation can be used for the estimation of the failure probability but the evaluation of limit states often requires expensive Finite Element Analysis (FEA) or Computational Fluid Dynamics (CFD) simulation. Therefore, alternate methods that make use of approximations are required for the estimation of structural failure probability. Using the methods that are available in the literature, the bounds on the failure probability of the system can be obtained. These bounds are obtained using approximation techniques, which are not accurate, leading to additional uncertainty in the bounds.

Therefore, to efficiently predict the failure probability of the structural system, the use of high quality function approximations for each of the limit states [2] and the joint failure surface are considered. Once the joint failure surface is approximated as a closed-form expression, the convolution integral can be solved efficiently using Fast Fourier Transforms (FFT) to estimate the structural failure probability. Due to the high non-linearity of the joint failure region, a methodology will be presented to solve this convolution integral based on multiple function approximations over several disjointed regions over the design space. The FFT technique uses a robust algorithm to solve the convolution integral accurately and efficiently resulting in a reliable estimate of the failure probability of the structural system. Numerical examples will be presented to show the applicability, efficiency and accuracy of the proposed method.

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STRUCTURAL-RELIABILITY-BASED ANALYSIS OF LARGE AND/OR COMPLEX SYSTEMS

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The probability that a large and/or complex system of interconnected facilities (e.g., power and water distribution networks and transportation systems) fails to perform in a satisfactory manner during and after an extreme event such as an earthquake or hurricane is naturally of interest. Structural-reliability-based procedures are well suited for such analyses because, in addition to providing an estimate of the probability that a system will fail, they also provide sensitivity information that can be used to identify those components within the system that are most critical to its performance. However, there are a number of algorithmic problems that must be resolved before available system-reliability-based analysis procedures can be efficiently applied to large and/or complex systems of components. For example, if the inclusion-exclusion rule is used to compute the probability of failure of a series system, then the required number of probability calculations increases geometrically with the number of components present in the system, thereby limiting the applicability of such an approach. This paper describes the required modifications to conventional structural-reliability-based calculations for the performance assessment of large and/or complex systems of components. Numerical examples are provided to illustrate the application of the proposed procedures.

STRUCTURAL RELIABILITY

RISK-BASED CONDITION ASSESSMENT AND MAINTENANCE ENGINEERING FOR AGING AIRCRAFT STRUCTURE COMPONENTS

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The paper illustrates how probabilistic physics-based models can be used for risk-based condition assessment and life prediction of aircraft components including the uncertainties in maintenance activities. Although this paper focuses on aircraft components under corrosion-fatigue damage, the proposed approach can be extended elsewhere to any machinery under progressive damage. Probabilistic modeling includes all significant uncertainties that affect aircraft component reliability, such as flight conditions, operational loading and environmental severity, manufacturing deviations, material properties and maintenance inspection activities. Maintenance uncertainties include those related to NDI techniques and operator's skills. The paper shows the uncertainty effects of different NDI techniques, maintenance intervals, operator skills, etc. on the engine reliability. Unscheduled maintenance rates are computed for given a maintenance schedule.

The proposed probabilistic approach to maintenance addresses two practical situations:

(i) Given scheduled maintenance strategy, compute component failure risks (unscheduled maintenance event rates) and the induced maintenance costs. This situation is useful to maintenance engineer for setting alarm levels for aircraft maintenance based on the actual failure risk tracking using recorded the on-line in-flight data and the off-line field/depot data.

(ii) Given component reliability, compute the optimal-cost scheduled maintenance strategy (inspection times). This situation is useful to design engineer for evaluating at the design stage the optimal-cost risk-based maintenance strategy. The design engineer can easily perform "what-if" analyses to compare the reliability and cost-effectiveness of different component designs including the maintenance activities and their induced costs.

The paper also shows how different damage mechanisms, namely LCF and Corrosion-LCF, influence the optimum maintenance strategy and impact on the average fleet failure risk. The paper illustrates how the average fleet failure risk evolution and maintenance cost are affected by different aircraft component fleet age distribution and by the quality of NDE inspection techniques.

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STRUCTURAL RISK CALIBRATION

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For more than 50 years the field of structural reliability has constrained itself to Alfred Freudenthal's concept of notional probabilities. This can be traced to the lack of proven models of both structural and load behavior in unusual situations, and the paucity of extreme value data. Yet society regularly makes trade-off decision of alternative investments and conflicting risks based on subjective probabilities and sociological perspectives of risk. It is time for the structural reliability field to move into the mainstream of asset allocation by accepting that subjectivity and perception are valid bases for calibrating alternatives. In taking this step it is incumbent upon engineering risk professionals to glean preferences from the wealth of knowledge reported by psychologists and sociologists on risk perceptions and preferences.

In this paper, the classic risk studies of Slovic [1] and others (e.g., [2] and [3]) are re-examined by analyzing them in terms of the similarity of each to built environment trade-offs. In this manner, the extensive social science literature can be used to establish initial guidance into the parameters of multi-attribute risk perception that are germane to structural safety calibration. These factors are then compared with some of the advancements taken by engineering risk professionals [4], [5].

Consideration of scale of event, perceived voluntariness of exposure, ubiquity and dread appear to be key attributes supplementing probability of occurrence and discounted consequence. Built environment risk management must incorporate these concerns into decision processes in order to enact effective risk reduction policies. A review of some effective practices [6] permits an analysis of how these have implicitly reflected the multiple attributes of risk. Finally, the issues of risk and risk perception as they affect the implementation of community policies for long-term low probability, high consequence events are discussed [7].

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RELIABILITY ANALYSIS FOR HUMAN'S COMFORT

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In the last three decades, special attention has been devoted to human response to tall buildings motions in order to take into account the comfort of the occupants [1]. For the range of frequency 1 to 80 hertz, the International Standard ISO 2631 (1978) has a set of limits of exposure to vibrations expressed in terms of rms of acceleration in order to attend three criteria: Preservation of working efficiency (given by the fatigue-decreased proficiency boundary curve), preservation of health or safety (exposure limit) and preservation of comfort (reduced comfort boundary). For vibrations in the frequency range 0.1 to o.63 hertz an addendum has been added to the International Standard (ISO 2631- 1978/Add.2 – 1982(E)). The exposure limit may be obtained doubling the allowable acceleration values. The reduced comfort boundary lies at one third of the corresponding levels of fatigue decreased proficiency boundary. A draft addendum to the International Standard ISO 2631/DAD 1 (1983) contains guidance on the application of ISO 2631 to human response to building vibration within the range 1 to 80 hertz.

Those criteria proposed by the International Standard ISO 2631 can be expressed analytically as
$fa^b=c$ where f is the frequency (hertz), a denotes rms of the acceleration, b and c are constant which depend on the frequency range. It is interesting to note that human fatigue (or comfort) is given by an expression similar to the well-known fatigue metal law.

When there are several discrete frequencies at which motion occurs, the linear accumulation discomfort (damage) hypothesis (Palmgren-Miner hypothesis) is tentatively suggested according to the following summation [1]:

$$\Sigma(a/a_f)$$

where a is rms of acceleration and a_f is the limit at the considered frequency. If the sum is less than unity, adverse comment is expected to be minimal.

This paper presents a technique to obtain the probabilistic structure of the stochastic discomfort process in terms of the probabilistic structure of the acceleration. The technique is similar to those for evaluate expected damage and the standard deviation of the damage in classical fatigue analysis. Closed expressions for the expected and the standard deviation of damage are derived for the stationary narrow-band acceleration random process.

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LOSS EXCEEDANCE CURVES FOR A PORTFOLIO OF STRUCTURES DUE TO EARTHQUAKES

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Loss exceedance curves for a portfolio of structures (i.e. buildings) due to potential future earthquakes provide the probabilities of exceeding a wide range of losses in a given time frame. Such curves are particularly important for the insurance and reinsurance industries. A computationally efficient methodology is proposed here to establish such curves without having to repeatedly run standard loss estimation codes such as HAZUS. It is assumed that information is provided about the geographical location, the local soil conditions and the type of each building in the portfolio. Fragility curves are also assumed to be known for every building type, incorporating uncertainties both in the seismic ground motion and building characteristics. The methodology addresses the important issue of geographic clustering of damage by incorporating appropriate damage correlation functions. An application is provided concerning the problem of determining the relative effectiveness of various seismic retrofitting solutions for the buildings in a given portfolio. Two different cases are examined: one considering and one excluding loss of human life.

EFFECT OF PHASE SPECTRUM UNCERTAINTY ON EARTHQUAKE MOTION

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The phase spectra of earthquake motions have not been important subjects although the modeling of amplitude spectra has claimed the attention of many researchers. Several pioneer works clarified the nonstationary characteristics of earthquake motions through the analyses of their phase characteristics. Osaki et al. [1] showed a similarity between the distribution width of the phase difference and the duration of earthquake motion. Izumi [2] who used the concept of group delay time, showed that the average arrival time of earthquake energy and the duration of earthquake motion can be evaluated by the mean and standard deviation of the group delay time. We also studied the phase characteristic of earthquake motions and proposed two models to simulate phase spectra. One is the modeling of phase spectra using the concept of group delay time and wavelet analyses, in which we proposed regression relationships in which the mean and the standard deviation of the group delay time were expressed as functions of epicenter distance and earthquake magnitude (Sato et al. [3]). The other is the modeling of phase spectra near the source region, taking into account the source rupture mechanism, propagating path and local soil condition (Sato et al. [4]). We also develop a method to simulate earthquake motion based on the modeled phase spectrum (Sato et al. [5]). Because the models developed to simulate phase spectra are statistical ones, we here evaluate effect of uncertainty of phase spectra on the time history and the Fourier amplitude of earthquake motions.

After introducing a stochastic model of phase spectrum defined by the concept of group delay time we analyze the effect of uncertainty of group delay time on time history of earthquake motion and its Fourier amplitude. The probabilistic characteristic of group delay time is expressed as a correlated multi-dimensional Gaussian distribution. By taking expectation of time history of earthquake motion with respect to group delay time the mean of the time history and Fourier amplitude are derived theoretically. The time history of variance of time history of earthquake motion is also derived. These results are verified by Monte Carlo simulation.

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APPLICATION OF STOCAHSTIC CHARACTERISTICS OF PHASE SEPCTRUM TO RANDOM VIBARATION ANALYSIS OF SDOF SYSTEM

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We have pointed out that a phase characteristic of earthquake motion strongly controls the non-stationary nature of earthquake motions and developed methods to model phase characteristics of earthquake motions[1]. In the analyses we use the concept of group delay time (the first order derivative of phase spectrum with respect to circular frequency) instead of Fourier phase spectrum, because a modeling the group delay time is much easier than directly modeling of phase spectrum. The mean of group delay time μ_{tgr} and its standard deviation σ_{tgr} are chosen as characteristic parameters, which represent an average arrival time of earthquake energy and a duration of earthquake motion, respectively. A regression equations of mean and standard deviation of group delay time of earthquake motions were derived as functions of earthquake magnitude and epicentral distance[1]. Based on our researches, the stochastic characteristics of group delay time at frequency ω have the Gaussian nature and defined by its mean and covariance along the frequency.

Because the time history of earthquake motion is affected by the uncertainty of group delay time we study here its effect on structural response. We derive theoretical solution of the time history of mean and root mean square (rms) response of a linear single degree of freedom structure exited by a non-stationary input ground motion in which random nature of the group delay time is expressed in an explicit form. The formulation is verified by the Monte Carlo simulation.

Some numerical simulations are conducted using this formula and yield the following results.

(1) Even if an amplitude spectrum of excitation is same, structural response is affected by the uncertainty of group delay time. Peak response of system becomes large as σ_{tgr} becomes small because the power of input motion concentrates in a short time range if σ_{tgr} is small. However if σ_{tgr} is beyond a certain large value, the response of system becomes similar to that of excited by white noise because the duration of input motion becomes longer.
(2) Effect of structural damping on the peak value of response is affected strongly by σ_{tgr} of input motion.
(3) To calculate the expectation of peak response time history from the rms time history we derive the empirical formula of peak factor through numerical simulation.

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EARTHQUAKE ENGINEERING: SESSION 1

GENERATION OF UNIFORM HAZARD GROUND MOTIONS USING HILBERT HUANG TRANSFORM

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A new procedure to generate Uniform Hazard Ground Motions (UHGM) for a particular site is proposed. It follows the general framework of Wen and Wu (2001) but uses new methods for simulation of ground motions based on available records and Hilbert Huang Transform proposed by Wen and Gu (2003).

The historic records of similar seismicity environment and soil class are first collected and classified into different bins according to their magnitude, distance, faulting mechanism, etc. The regional seismicity statistics such as occurrence rate, magnitude and spatial distribution are utilized to generate an event random in time and space. For each event a corresponding bin is chosen. Then one of the records in this bin is randomly picked and simulated using the new methods proposed by Wen and Gu (2003). The methods are based on the Hilbert Huang Transform (Huang et al 1998) and can closely reproduce the intensity and spectral content change with time of the ground motions.

The Uniform Hazard Response Spectra (UHRS) for a given probability level can be constructed from the spectral accelerations of a large pool (thousands) of simulated ground motions. The UHGMs are then selected from the pool by matching the ir spectra with the UHRS for all frequencies in a least square sense.

An example is given for Santa Barbara, California. The results are compared with the UHRS according to the procedures in USGS National Seismic Hazard Project (1997) and the SAC project (2001).

The advantages of the new procedure are:
1. It reproduces the non-stationarity of the ground motions.
2. It fully uses the historical records and does not rely on theoretical or empirical models, thus it preserves the jagged look of spectrum and the variability across the ensemble.
3. Unlike deaggregation method, it considers all the possible events and the faulting mechanisms, and the ground motions can be applied to systems of different frequenc ies.
4. It does not scale records, thus preserves the physical relationship between ground motion and earthquake characteristics, distance, and soil condition.
5. It bypasses the need for analytical attenuation laws and theoretical ground motion models.

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MACRO-SPATIAL CORRELATION STRUCTURE OF SEISMIC GROUND MOTIONS OF THE 1999 CHI-CHI EARTHQUAKE

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Evaluating macro-spatial correlation of seismic ground motion for regional seismic risk management is very important for earthquake damage prediction and portfolio analyses in which simultaneous damage in different sites has to be taken into consideration.

Taking account of seismic damage of building portfolio, infrastructures spread spatially and so on, simultaneity of the ground motion intensity in different sites should be properly treated. Utilizing empirical attenuation laws, in particular, not only their mean characteristics of the uncertainty of the laws but also the spatial correlation structure have to be adequately modeled. Past researches, however, made intuitive assumptions: perfectly correlated or perfectly uncorrelated of the uncertainty attenuation laws used. This correlation must be dependent upon many factors such as relative distance between two different sites, ground conditions of the sites, direction of propagating waves. No past research on quantifying the spatial correlation structures of ground motion intensity at different sites.

Mean attenuation characteristic of ground motion induced from the seismic source can be conveniently estimated by using the mean attenuation laws, focused on in this study is spatial correlation structure of the deviatoic component (uncertainty) from the mean value. To model the correlation structure, dense array observation of earthquake records in Taiwan island which has been published in CD-ROM is fully used.

In this paper, focused on is the residual value between observed and predicted ground motion. The spatial correlation of the residual value is modeled assuming that the correlation depends only on the relative distance between two different sites. The strong motion records of the 1999 Chi-Chi Earthquake are used for this analysis since very high-dense observation has been made throughout Taiwan island. As the results, the correlation length which represents the spatial correlation is found from 14 to 30 km for this particular earthquake event in Taiwan. It is, however, necessary to note that this model is valid only for this particular earthquake and its validity should be checked for other earthquake events as well as for other different regions.

Finally, the paper will show several application area where the proposed model can effectively be used.

DECOUPLED METHODOLOGY FOR PROBABILISTIC DESIGN OPTIMIZATION

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Reliability-based design optimization is a methodology of finding designs that are characterized by a low probability of failure. During the last few years, a variety of different approaches have been developed for performing reliability-based design optimization. Traditionally, reliability based design optimization is formulated as a nested-optimization problem. The inner loop, generally, involves the solution to optimization problems for computing the probabilities of failure of the critical failure mechanisms or the probability of failure of the system and the outer loop performs optimization by varying the decision variables in order to minimize an objective function and satisfy the constraints. Such a formulation is by nature computationally intensive, requiring numerous function and constraint evaluations. To alleviate this problem, researchers have developed sequential reliability-based design optimization formulations. These methods perform deterministic optimization and reliability assessment in a sequential manner until a consistent reliability-based design is obtained. The sequential methods are attractive because a consistent reliable design can be obtained at considerably low computational costs. However, the designs obtained by using existing sequential methods does not address the problem of obtaining a true local optimum. *In this paper, a new sequential method for reliability-based design optimization will be developed. In the proposed method, the sensitivities of the Most Probable Point (MPP) of failure with respect to the decision variables are introduced to update the MPPs during the deterministic-optimization phase of the sequential RBDO approach. The proposed method will be shown to find the true local optimum.* The proposed methododology will be illustrated through numerical test problems.

RELIABILITY-BASED OPTIMAL DESIGN IN OPENSEES

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Traditionally, structural design has been based on engineering judgment and experience, usually resulting in conservative designs. Advances in computational methods and resources, together with new developments in structural reliability and optimization theories, have opened new possibilities for improved design methods that incorporate considerations of reliability and optimization.

In this paper, the developments in [1] are implemented in a modern software framework for finite element reliability analysis [2,3]. This enables reliability-based design optimization for comprehensive real-world structural examples. The problem of minimizing the initial cost of the design plus the expected cost of failure subject to reliability and structural constraints is considered. The solution approach employs a reformulation of the optimization problem into a deterministic, semi-infinite optimization problem. This is solved in conjunction with separate reliability calculations. An important advantage of the approach is that the optimization and reliability calculations are decoupled.

The object-oriented programming approach is employed in the computer implementations. This renders a transparent software design that is easy to maintain and extend. The advantage of this approach is emphasized in the implementation of the decoupling approach in the optimization analysis. Due to the object-oriented software architecture the analyst may readily combine different algorithms that are implemented to solve the optimization problem and the reliability problem.

A comprehensive numerical example of a real-world structure is presented to demonstrate the use of the implemented methodology. Material properties and loads are characterized as uncertain while geometry parameters are subject to design optimization.

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STOCHASTIC OPTIMIZATION IN ENGINEERING DESIGN: SESSION 1

AN RSQP APPROACH FOR A SINGLE-LEVEL RELIABILITY OPTIMIZATION

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In reliability-based design optimization (RBDO) the evaluation of the reliability constraints involve the solution of an optimization problem [1]. This bi-level nature of most RBDO formulations can be too expensive to be implemented in some practical optimization problems, where a single function evaluation can range from minutes to hours or even days. Some authors have investigated the use of single-level RBDO formulations. In [2] the authors reformulate the problem as a semiinnite optimization problem and in [3] a further analysis of this strategy is described.

An interesting approach is the one proposed in [4, 5] in which the optimization problem required to evaluate each reliability constraint is replaced with its corresponding first-order optimality conditions. As a result the dimensionality of the problem suffers an increment in the number of design variables and equality constraints. This formulation is extended in [6] for a performance measure approach (PMA) implementation of the reliability constraints.

This new optimization problem consists of some design variables and many auxiliary variables which are local instances of the random parameters corresponding to each reliability constraint. This structure holds much similarity to the one that arises in a simultaneous analysis and design (SAND) formulation for optimization of problems governed by PDEs (see for example [7]). In SAND, the system of equations resulting from the discretization of the problem is solved at the same time as the optimization. A small number of design variables is augmented by a large number of state variables and their corresponding system of equations as equality constraints. Solutions to this problem is the use of reduced-Hessian methods based on a sequential programming approach as in [7].

In this paper, ideas from the research of rSQP methods for SAND will be explored for the unilevel reliability optimization formulation presented in [6]. Numerical implementations and example problems will complement the paper.

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RELIABILITY-BASED DESIGN OPTIMIZATION OF STRUCTURAL SYSTEMS

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A new method for optimizing structural systems based on sampling techniques is derived. The method utilizes an approximate expression for the system failure probability. This expression can be made arbitrarily accurate without significant increase in computing time. Hence, the approximation introduced is not of practical importance. The expression for the system failure probability gives rise to an approximate optimal design problem, which is solved using an algorithm based on sample average approximations. The algorithm utilizes adaptive sampling techniques to reduce the computing time. A numerical example illustrates the method.

STOCHASTIC OPTIMIZATION IN ENGINEERING DESIGN: SESSION 1

RELIABILITY-ORIENTED OPTIMIZATION UNDER COMBINED LOADING

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Reliability-oriented optimization can be performed in a one-level approach, where the first order Kuhn-Tucker optimality conditions for the design point of the reliability problem are added as constraints to the cost-benefit optimization problem using first order reliability methods (FORM) in standard space. Solution techniques have been developed for component and series system problems in time-invariant and time-variant case using stationary and locally non-stationary load models. A wide range of objective functions for discounted cost benefit optimization based on a continuous renewal model for a series of cases has been derived [3], [4].

A differentiable acceptability criterion derived from the Life Quality Index [2] can be added as constraint to the optimization task in order to make sure that the optimal structure is also acceptable. In this paper the effect of different load situations on the optimal solution using the acceptability criterion will be shown.

The one-level approach will be extended to a more realistic load situation of stationary rectangular wave renewal (jump) processes and differentiable Gaussian processes with intermittencies using the coincidence method [1] to evaluate the outcrossing rates and failure probabilities of structural components. It is then possible to consider for example intermittent climatic loadings (wind, snow,…) or long and short term imposed loads. Different load cases are characterized by the coincidence probabilities computed from the interarrivalduration intensities of the load processes. In the one level approach all load combinations can be treated in one optimization task. This is independent from the proposed renewal or maintenance strategy. The outcrossing approach will be used assuming a Poissonian distribution of the failure events. Some algorithmic details are explained. The approach is demonstrated at an example.

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THE COMPUTATION OF BOUNDS FOR ENERGY RELEASE RATES IN FRACTURE MECHANICS

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We present an *a-posteriori* method for computing rigorous upper and lower bounds of the J-integral in two dimensional linear elasticity. The J-integral and the tensor product integral, which are typically expressed as contour integrals, are recast as a surface integral which yield a quadratic continuous functional of the displacement. By expanding the quadratic output about an approximate finite element solution, the output is expressed as a known computable quantity plus linear and quadratic functionals of the solution error. The quadratic component is bounded by the energy norm of the error scaled by a continuity constant, which is determined explicitly. The linear component is expressed as an inner product of the errors in the displacement and in a computed adjoint solution, and bounded using standard a-posteriori error estimation techniques. The method is several fracture problem in plane strain elasticity.

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MODEL VALIDATION AND UNCERTAINTY QUANTIFICATION: SESSION 2

BAYESIAN VALIDATION OF STATISTICAL MODELS

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This paper presents a Bayesian methodology for validating computational models under physical, informational and model uncertainties. The prior distribution of model response is updated based on experimental observation using Bayesian analysis. The prior and posterior distributions are then used to compute a validation metric that judges the validity of model prediction. This concept is extended in this paper for validation of statistical models (distributions) using samples of test data. Classical and Bayesian hypothesis testing methods are compared for their application in model validation.

The paper also investigates the quantification of model form error. While methods are available to quantify model uncertainty using multiple models, this paper discusses model form error estimation from a single model. Model form error is treated as a random variable and the distributions of statistics of the model form error are then obtained from bootstrapping the available data. The proposed method is illustrated for a practical problem involving mechanical properties of joints found in weapons systems and their structural response under dynamic loading.

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MODEL PARAMETER UPDATING USING BAYESIAN NETWORKS

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This paper outlines a model parameter updating technique for a new method of model validation using a modified model reference adaptive control (MRAC) framework with Bayesian Networks (BNs). The model parameter updating within this method is generic in the sense that the model/simulation to be validated is treated as a black box. It must have updateable parameters to which its outputs are sensitive, and those outputs must have metrics that can be compared to that of the model reference, i.e., experimental data. Furthermore, no assumptions are made about the statistics of the model parameter uncertainty, only upper and lower bounds need to be specified.

This method is designed for situations where a model is not intended to predict a complete point-by-point time domain description of the item/system behavior; rather, there are specific points, features, or events of interest that need to be predicted. These specific points are compared to the model reference derived from actual experimental data. The logic for updating the model parameters to match the model reference is formed via a BN. The nodes of this BN consist of updateable model input parameters and the specific output values or features of interest. Each time the model is executed, the input/output pairs are used to adapt the conditional probabilities of the BN. Each iteration further refines the inferred model parameters to produce the desired model output. After parameter updating is complete and model inputs are inferred, reliabilities for the model output are supplied. Finally, this method is applied to a simulation of a resonance control cooling system for a prototype coupled cavity linac. The results are compared to experimental data.

MODEL VALIDATION AND UNCERTAINTY QUANTIFICATION: SESSION 2

QUANTIFYING TOTAL UNCERTAINTY USING DIFFERENT MATHEMATICAL THEORIES IN A VALIDATION ASSESSMENT

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A grassroots *uncertainty quantification* team at LANL is developing a new metric to quantify the uncertainties in the process of validating computer codes/models with experiments. Inherent in *validation* activities is the understanding, characterization and propagation of different kinds of *uncertainties*, arising from sources such as model uncertainties, numerical errors, parameter uncertainties, and lack of knowledge. In assessing *uncertainty*, we distinguish between two general types. The first is the natural variability of things due to stochastic processes such as manufacturing processes—called *variability*—cannot be reduced, but is straightforwardly quantified. Another type of uncertainty is that due to a lack of specific information—called *complexity*—can be reduced with the acquisition of more information / knowledge. *Total uncertainty* is a combination of these two.

We will illustrate the development of *total uncertainty* on a simple experiment and modeling project. In this development we demonstrate how two different kinds of uncertainty (complexity arising from model uncertainty and variability arising from experimental test data) can each be described using different mathematical theories of uncertainty (possibility and probability), and how they can be combined for assessing *total uncertainty*. Assessing total uncertainty is a fundamental step in the development of a metric for validation.

PERFORMANCE-OPTIMAL AND UNCERTAINTY-ROBUST DECISIONS OF THE LOS ALAMOS PROJECT-Y

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In April 1943, the wartime project-Y, also known as the "Manhattan project," was tasked with the development of a new type of weapon based on the principle of nuclear fission. Physicists and engineers were gathered in Los Alamos, New Mexico, and provided with a series of five lectures detailing everything that was known at the time about the possibility of developing a practical military weapon using a fast neutron chain reaction. The lectures were assembled in a document known as the Los Alamos Primer, and subsequently declassified by the U.S. Government in 1965[1].

When the project-Y was initiated, many physical properties of the nuclear materials were uncertain. Likewise, knowledge about some of the physical processes involved in nuclear fission was to great extent unknown. To alleviate the lack-of-knowledge, conservative assumptions were made. It is often suggested that empirical performance optimization practices made possible the successful completion of the project. Even though the advent of computational resources and numerical methods have changed much of the scientific landscape, contemporary approaches to design in physics and engineering still rely on practices such as calibration and performance optimization.

This paper surveys the sources of uncertainty reported in the Los Alamos Primer and other pre-1943 documentation. Using the "Little Boy" weapon as an example for calculations, it is argued that this design is not performance-optimal, as commonly thought. Instead, it offers some degree of robustness to uncertainty and lack-of-knowledge, while "satisficing" performance—that is, making it just "good enough." This conclusion is reached by performing a formal analysis of the trade-off between performance and robustness-to-uncertainty. Because many of the sources of uncertainty identified do not accommodate a probabilistic description, the analysis is carried out through the theory of information-gap, which only requires convex models of uncertainty[2].

Implications for modern decision-making such as the accreditation of numerical simulations (also referred to as model verification and validation) and the certification of engineered systems are two-fold. First, conservatism could be avoided to a great extent, if more emphasis were placed on exploring the trade-off between performance-requirement and robustness-to-uncertainty. Second, decision-making frameworks exist that do not, unlike probabilistic-based reliability methods, artificially restrict the representation of uncertainty or lack-of-knowledge to a strict probabilistic one.

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PERCOLATION THEORY APPROACH TO QUANTIFY GEO-MATERIAL DENSITY-MODULUS RELATIONSHIPS

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Percolation Theory (PT) provides a quantitative means to relate geo-material porosity, and thus density, with the material modulus. Geo-material modulus can be measured in-situ using field seismic testing that relates modulus to seismic velocity (low strain modulus), or laboratory testing and correlations for high strain modulus. Elastic modulus, as quantified by PT, varies universally as a function of the difference between the material porosity and a threshold porosity more generally described as the percolation threshold. Two characteristic modulus behaviors, physical gel and chemical gel, exist in PT. Fractured, weathered rock masses such as weathered granites, where fracturing significantly effects mass behavior, and dense, well graded cohesionless granular materials tend to behave as physical gels. Cohesive and cemented soils, and intact, porous rock such as limestones and tuffs tend to behave as chemical gels. PT modulus-porosity relationships are shown to be consistent with testing of recovered rock core and with test results presented in the literature. Porosity-modulus trends are consistent for geo-materials from soils to weathered, fractured rock. Among other uses, these relationships permit estimating unit weights of in-situ geo-material masses for earthwork determinations in highway construction, and general geo-material mass characterization.

A DYNAMICAL SFE METHOD IN THE FREQUENCY DOMAIN

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The study of uncertain structures has become more and more important in these last years. The uncertain structures are characterized by the fact that one or more of their mechanical and/or geometrical properties must be defined probabilistically. The importance of this kind of study is above all related to some structural problems, as the structural reliability, for which neglecting the effective stochastic nature of the structural parameters is not possibile. It is obvious that for these systems the traditional deterministic analysises cannot be applied, but probabilistic approaches have to be taken into account. Among these, the statistic approaches, based on the Monte Carlo simulations, are the simplest from a theoretical point of view. In fact, they need the realizations of a sufficiently great number of samples of the uncertain parameters and the solution of the corresponding deterministic problems. However, increasing the structural degrees of frredom and the number of uncertain parameters, the computational effort related to the statistic methods becomes greater and greater. For this reason, some alternative non-statistic methods have been proposed in the literature [1,2]. In particular, the perturbative approaches have had the greatest diffusion. As a consequence, the stochastic finite element (SFE) approach is usually identified with the classical FE approaches coupled with the perturbation techiques. This happens in both the static and dynamic field [3-6]. The fundamental drawback related to the use of the perturbative approaches lies on the consistent lost of accuracy when the level of uncertainty of the structural parameters increases. Consequently the results obtained by these approaches are acceptable only for very low level of uncertainty.

Other non-statistic approaches in the literature are based on the expansion methods of the structural stiffness matrix in order to perform explicitly its inversion. Some authors have used the Neumann expansion, both in the static case [7,8] and in the dynamic case [9]. At last, in some works, the chaos expansion is used [10,11]. A common drawback common to all these approaches is that a sufficient accuracy is reached only for low levels of uncertainty.

Recently a non-statistic non-perturbative method has been proposed for the static analysis of uncertain FE discretized uncertain structures [12]. This method takes into account the properties of the natural deformation modes of the FE type used for the discretization. It is characterized by eccellent performances both in terms of accuracy (very good, for high level of uncertainty, too) and in terms of computational efficiency.

Aim of the present work is extending to the dynamic field the fundamental characteristics and properties of the above cited approach. The goal is to define a dynamical SFE approach with eccellent properties of accuracy and computational efficiency. The analysis is performed in the frequency domain.

In particolar, here, the explicit relationships between the dynamical response in the frequency domain and the random variables characterizing the structural parameter uncertainty (commonly named performance functions in the static case in the field of the response surface approaches) are given in a very accurate approxiamated form. The knowledge of these relationships allows us to esily cheracterize the response from a probabilistic point of view once that the kind of stochasticity of the structural parameters are defined.

PROBABILISTIC MATERIAL CHARACTERIZATION AND ANALYSIS: SESSION 2

ATOMISTIC SIMULATION FOR STUDYING THE ASYMPTOTIC BEHAVIOR OF ULTIMATE STRENGTH OF CARBON NANOTUBES WITH RANDOMLY OCCURRING DEFECTS

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While CNTs are found to have ultra-high stiffness and strength, an enormous scatter is also observed in available laboratory results. This paper studies the effects of randomly distributed Stone-Wales (SW or 5-7-7-5) defects on the mechanical properties of single-walled nanotubes (SWNTs) using the technique of atomistic simulation. A Matern hard-core random field applied on a finite cylindrical surface is used to describe the spatial distribution of the SW defects. We simulate a set of displacement controlled tensile loading up to fracture of SWNTs with (6,6) armchair configuration and aspect ratios between 6.05 and 24.2. A modified Morse potential is adopted to model the interatomic forces. Ultimate strength is calculated from the simulated force time histories. The asymptotic behavior of the ultimate strength of SWNT with defects as tube length, l, increases is discussed. The distribution shifts to the left and becomes narrower with increasing l and appears to fit the Weibull distribution rather well.

PROBABILISTIC FATIGUE LIFE ESTIMATION OF SEEDED UDIMET 720 SUPERALLOY SPECIMENS

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Powder superalloy metals such as UDIMET-720 are known to have high fatigue lives as well as high strength and ductility under extremely high temperatures. These properties make these superalloys especially suitable for use in gas turbine disks. However, despite high quality controls instituted during metal processing, sufficiently high numbers of ceramic inclusions materialize within the matrix, creating weak links where fatigue cracks initiate. To study the effect of such ceramic inclusions on the fatigue lives of gas turbine disks, an experimental program has been initiated at NASA Glenn Research Center as part of the Crack Resistant Disk Materials task within the Ultra Safe Propulsion Project. Batches of powder metals were intentionally seeded with alumina to increase the chances of encountering inclusions within test specimens. The seeded specimens were then tested at various fatigue stress ranges and maximum stress amplitudes. The tests were interrupted at various stages of loading to monitor surface crack initiation and propagation. A statistical analysis of the data was performed, the results of which were subsequently implemented in a Monte Carlo simulation. The simulation is used to obtain probabilistic estimates of the expected fatigue life of these materials. The simulation illustrates how the distribution of fatigue lives is affected by the stress ranges and stress amplitudes. The model accounts for the effect of residual stresses near the surface and the size and orientation of the inclusions.

PROBABILISTIC MATERIAL CHARACTERIZATION AND ANALYSIS: SESSION 2

APPLICATION OF PROBABILISTICS MODELS FOR THE QUANTIFICATION OF THE FATIGUE CRACK GROWTH

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Fatigue is known to be a major cause of failure of a large number of structural components. From a fracture mechanics point of view, fatigue damage of a component subject to dynamic loading can be measured by the size of the dominant crack, and failure occurs when this crack reaches a critical size. It is widely recognized that fatigue crack growth is fundamentally a random phenomenon that can only be quantified in terms of probability and statistics. The two main reasons for the randomness in fatigue crack growth behavior are the random material resistance to fatigue crack growth and the random loading. The goal of this work is to describe the statistical behavior of the parameters that control the fatigue crack growth and quantifying the influence of such parameters on the life of the structural component. In this sense, the Monte Carlo method, FOSM and ASM methods were implemented and applied in a structural problem and the probability of failure was calculated. Since the Monte Carlo regards of an exact method, it was used to be compared with the rest of the methodologies.

Keywords
Reliability, Fracture, Probabilistic Modeling, Fatigue Crack Growth.

A PROBABILISTIC APPROACH TO UNCERTAINTY QUANTIFICATION WITH LIMITED INFORMATION

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Many safety assessments rely on probabilistic characterizations about which there is incomplete knowledge. For example, a given system may depend upon the time to failure of a piece of equipment for which no failures have actually been observed. In such a case, analysts are faced with the task of developing a failure model for the equipment in question, having very limited knowledge about either the correct form of the failure distribution or the parameters that characterize the distribution. They may assume that the process conforms to a Weibull or log-normal distribution or that it can be characterized by a particular mean or variance, but those assumptions impart more knowledge to the analysis than is actually available. To address this challenge, we propose a method where random variables comprising equivalence classes constrained by the available information are approximated using polynomial chaos expansions (PCEs). The PCE approximations are based on rigorous mathematical concepts developed from functional analysis and measure theory. The method has been codified in a computational tool, AVOCET, and has been applied successfully to several example problems.

One such problem involves a hypothetical safety system in which one weak link and one strong link are exposed to a high-temperature fire environment. If the weak link fails before the strong link, the system is deemed to fail in a safe manner, but if the opposite occurs, there is a loss of assured safety (LOAS). There are known equations to describe the temperature response of each component as a function of known distributions to determine the failure probability of each time, and component as a function of temperature. However, each equation and distribution has multiple parameters about which there is incomplete, and sometimes conflicting, information. The problem is to develop an uncertainty characterization of the probability of LOAS (the output) that is consistent with the information available about the parameters of the response equations and failure distributions (the inputs).

The problem, originally proposed and solved by Helton et al. using evidence theory, was addressed within AVOCET using PCEs. Results from AVOCET include a set of many distributions that collectively describe the epistemic uncertainty in the output probability of LOAS. As expected, these distributions are fully contained within the plausibility and belief functions obtained from evidence theory. The distributions from AVOCET tend to approach the bounds from evidence theory when similar assumptions and approximations are made regarding the intervals within which the uncertain parameters may lie.

The results from this and other examples further indicate that the method used in AVOCET should be applicable to a broad range of engineering problems having diverse characterizations of aleatory and/or epistemic uncertainties.

STRUCTURAL RELIABILITY APPLICATION OF CORRELATION IN RANDOM-SET VALUED VARIABLES

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Much attention has been recently paid to generalized theories of probability for modeling epistemic uncertainty. Engineering applications started appearing in the literature in the second half of the 1990s. This paper addresses one prominent issue in the still evolving field of generalized theories of probability, namely the meaning and importance of correlation between random variables within Random Set Theory (RST).

RST provides the capability to accommodate imprecise or set-valued measurements, and represents a generalization of the classical probability theory of point-valued random variables. RST leads to the calculation of upper and lower probability distributions that are consistent with the available information and do not require additional assumptions.

The meaning and importance of correlation is investigated through the use of a multi-valued mapping from a finite set of random variables to itself. The multi-valued mapping represents the abovementioned imprecision. The definition of correlation is thus naturally extended through the multi-valued mapping to a random relation.

The paper describes the application of this approach to two structural loads constrained by a random relation and to the behavior prediction for a simple structure subjected to these two loads.

TIME SERIES ANALYSIS WITH NON-PRECISE DATA – PART I

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The results of measurements of continuous quantities contain essentially two different types of uncertainty: randomness and imprecision. In modeling, the dominating concept to describe uncertainty is using stochastic models which are based on probability. However, in probabilistic models only randomness is considered whereas the imprecision of data is ignored. Imprecision appears for example as a result of the limited precision of measuring instruments or model errors and is not statistical in nature. Besides this, many data are imprecise by nature: Recovering times, life times, or human reliabilities cannot be described realistically by a real-valued number. The quantification of the imprecision is possible by using so-called non-precise numbers, which are a generalization of real numbers. They are defined and represented by so-called characterizing functions, see [1].

Time series of measurements of continuous quantities, which are observed in practice, are afflicted with imprecision. Therefore, the single observations should be modeled by using non-precise data. In order to analyze a time series of non-precise observations, the well known methods for the analysis of real-valued time series have to be generalized to this situation. In this context, an introduction to the generalization of fundamental methods in real-valued descriptive time series analysis for non-precise data and their investigation is given. For example, the well known methods of moving average, exponential smoothing, and the simple time series model with trend and seasonal component are analyzed. One result of this investigations is, that for some methods the application of the extension principle yields to poor results. In these cases, new methods have to be developed.

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GENERALIZED MODELS OF UNCERTAINTY FOR ENGINEERING MECHANICS: SESSION 1

TIME SERIES ANALYSIS WITH NON-PRECISE DATA – PART II

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In the first part, the generalization of fundamental methods of real-valued descriptive time series analysis to the situation of non-precise data was explained and investigated. For these methods, no stochastic background was used to analyze the data.

Considering time series with non-precise observations as realizations of a stochastic process with non-precise values, the generalization of methods of stochastic time series analysis is possible by using so-called fuzzy random variables. In the literature, there are different proposals for the definition of fuzzy random variables (for example the definition of Kwakernaak in 1978 and the definition of Puri and Ralescu in 1986) and their characteristic values like expectation and variance.

In the contribution, a short introduction to fuzzy random variables, similar to the definition of Puri and Ralescu [2], is given. Furthermore some characteristic values for fuzzy random variables are defined. For example, the expectation and the variance are defined by using the approach of Fréchet, see [1]. For the analysis of time series of non-precise observations, special attention will be given to the field of linear approximation and linear forecasting.

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SAMPLE-INDUCED SIMULATION OF FUZZY RANDOMNESS

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In this paper, a new sampling method for both real valued random variables and fuzzy random variables is presented and formulated as sample-induced simulation technique. This method directly processes the information contained in the sample. The formulation and determination of distribution functions are dispensed with. Statistical estimations are no longer necessary. The sample-induced simulation technique operates free of a model that specifies stochastic properties. This is a major advantage, in particular, as a sophisticated stipulation of fuzzy probability distributions and a simulation based on these are problematic. Moreover, the new sampling method is able to take account of randomness and fuzziness simultaneously. The natural uncertainty of input data may be taken into consideration close to reality. The aim of the sample-induced simulation technique is to combine the benefits of simulation techniques [2] with those of the generalized uncertainty model fuzzy randomness [1] and, simultaneously, to bypass weaknesses when specifying uncertainty models for data observed.

The sample-induced simulation technique is based on the following two-stage approach. In the first stage a sample induced estimation is carried out. The concept of estimation is thereby applied in a generalized sense. The basic idea behind this estimation is to describe the characteristics of a universe by a sufficiently large sample rather than by the conventional method of using a probability distribution function. Starting point is the observed (fuzzy) sample S_0 (fuzzy sample = sample whose elements are fuzzy variables) of size n_0. A second concrete (fuzzy) sampleS_1 of a considerably larger size $n_1 » n_0$ is then sought that represents the original sampleS0 "as well as possible", i.e., exhibits statistical characteristics comparable to S_0. The second stage consists in the simulation itself. The hitherto conventional simulation on the basis of estimated distribution functions may be dispensed with; the new sample S_1 now contains the n1 input vectors for the n1-fold numerical structural analysis – for the case of an elementary approach.

The paper focuses on describing the basic idea of the sample-induced simulation technique and demonstrates the capacity of this new method by way of an example.

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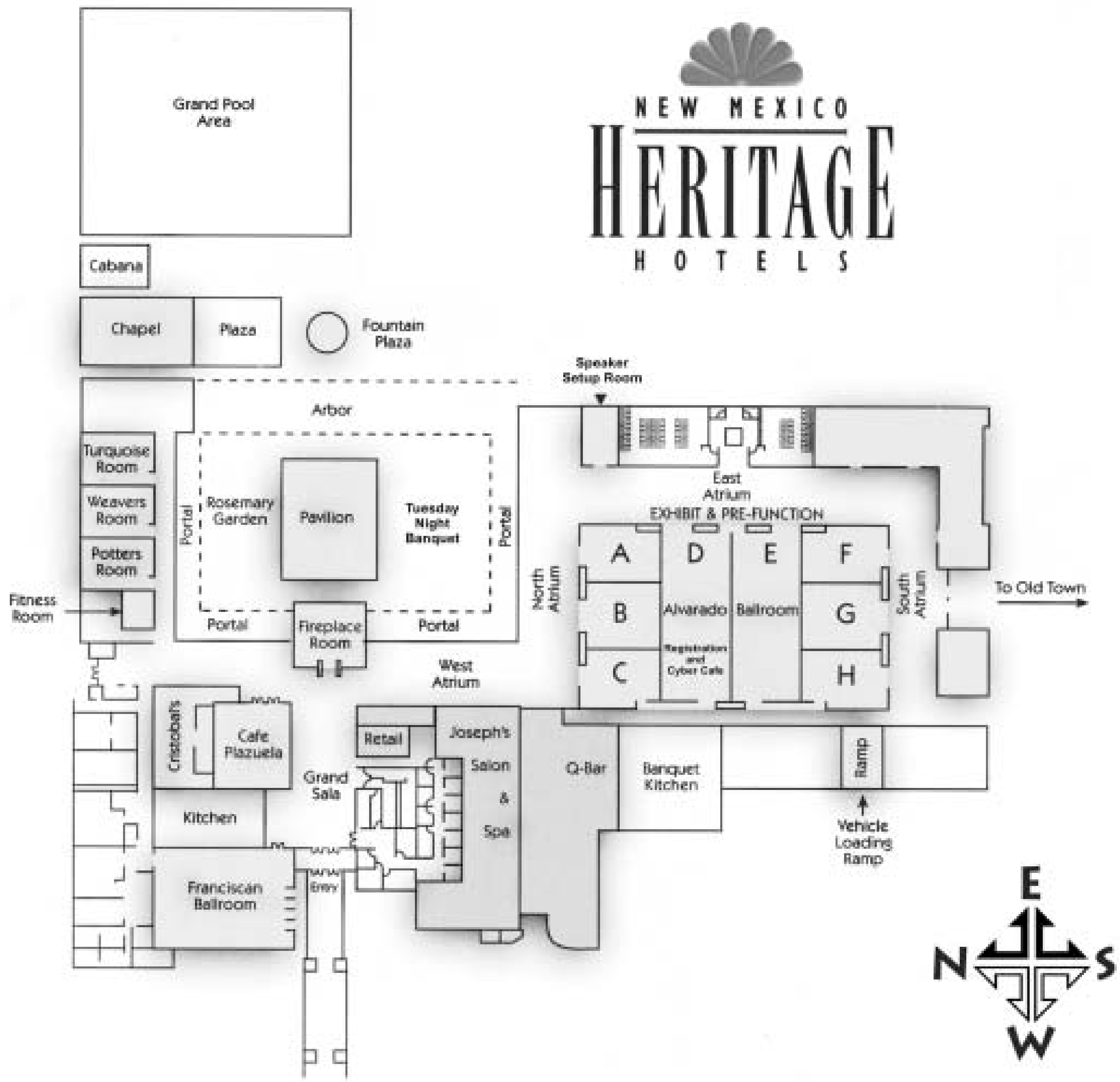
Grand Pool Area
Cabana
Chapel
Plaza
Fountain Plaza
Arbor
Turquoise Room
Weavers Room
Potters Room
Fitness Room
Portal
Rosemary Garden
Pavilion
Tuesday Night Banquet
Portal
Portal
Fireplace Room
Portal
West Atrium
Speaker Setup Room
East Atrium
EXHIBIT & PRE-FUNCTION
North Atrium
A
B
C
D
E
F
G
H
Alvarado Ballroom
Registration and Cyber Cafe
South Atrium
To Old Town
Cristobal's
Cafe Plazuela
Kitchen
Grand Sala
Franciscan Ballroom
Entry
Retail
Joseph's Salon & Spa
Q-Bar
Banquet Kitchen
Ramp
Vehicle Loading Ramp
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NEW MEXICO
HERITAGE
HOTELS

Tuesday Technical Program: 3:30 – 5:30 PM

ROOM	**Technical Session Title**
Ballroom A	Computational Methods in Reliability Analysis
Ballroom B	Mechanics of Random Media *
Ballroom C	Earthquake Engineering: Session 2
Ballroom F	Stochastic Optimization in Engineering Design: Session 2 *
Ballroom G	Model Validation and Uncertainty Quantification: Session 3 *
Ballroom H	
Turquoise	Generalized Models of Uncertainty for Engineering Mechanics: Session 2 *

** Sessions Organized by ASCE Probabilistic Mechanics Committee*

Technical Program: Tuesday, July 27: 3:30 – 5:30 PM				
Time 24 Min. Talks (* Speaker)	Room: Ballroom A **Computational Methods in Reliability Analysis** Session Chairs: Eldred, M., Riha, D.	Room: Ballroom B **Mechanics of Random Media** Session Chairs: Graham Brady, L., Arwade, S.	Room: Ballroom C **Earthquake Engineering** **Session 2** Session Chairs: Conte, J., Smyth, A.	Room: Ballroom F **Stochastic Optimization in Engineering Design** **Session 2** Session Chairs: Royset, J., Trucano, T.
3:30	Investigation of Reliability Method Formulations in DAKOTA/UQ Eldred, M.*, Agarwal, H., Perez, V., Wojtkiewicz, S., Renaud, J.	Simulation of Random Heterogeneous Materials Koutsourelakis, P.*	Time-Frequency Localization in Stochastic Seismic Models Via Time-Frequency Atoms Spanos, P.*, Politis, N., Thomaidis, P.	Structural Optimization Using Inductive Identification Trees Igusa, T.*, Liu, H.
3:54	Robust Most Probable Point Search Algorithm for Difficult Performance Functions Riha, D.*, Thacker, B., Kong, J., Huyse, L.	Analysis of Material Property Fields for Heterogeneous Materials Baxter, S.*, McNeill, S., Graham Brady, L.	Seismic Fragility Analysis Kafali, C.*, Grigoriu, M.	Identification of Critical Components and Cutsets Using Linear Programming Bounds on System Reliability Song, J.*, Der Kiureghian, A.
4:18	Moment-Based Stochastic and Dimension-Reduction Methods for Structural Reliability Analysis Rahman, S.*, Xu, H.	Nonlocal Modeling of Heterogenous Multiscale Systems Shi, J.*, Ghanem, R.	Fragility of Steel Moment Frames with Novel Beam-To-Column Connections Utilizing Shape Memory Alloys Taftali, B.*, Ellingwood, B. R., DesRoches, R.	Time-Variant Reliability Analysis Using a Direct Search Optimization Method Joanni, A. E.*, Rackwitz, R.
4:42	Reliability Analysis In High Dimensions Adhikari, S.*	A Stochastic Micromechanical Model for the Behavior of Heterogeneous Materials Williams, T.*	Estimation of Fragility Curve by Using Limit Seismic Intensity and Markov Chain Monte Carlo Yoshida, I.*, Sato, T.	Seismic Disgn Optimization Using LCC-Based Risk Index Takahashi, Y.*
5:06	Linkage Genetic Algorithm for Reliability Analysis of Structural Systems Wang, J., Ghosn, M.*	Translation Vectors with Non-Identically Distributed Components: Application to Heterogeneous Materials Arwade, S.*	A Probabilistic Evaluation of the Seismic Response of a City Lombaert, G.*, Clouteau, D.	

Technical Program: Tuesday, July 27: 3:30 – 5:30 PM				
Time 24 Min. Talks (* Speaker)	Room: Ballroom G **Model Validation and Uncertainty Quantification** **Session 3** Session Chairs: Huyse, L., Paez, T.	Room: Ballroom H	Room: Turquoise **Generalized Models of Uncertainty for Engineering Mechanics** **Session 2** Session Chair: Beer, M., Tonon, F.	
3:30	Development of a MCT Based Virtual Testing Tool for Progressive Damage Predictions of Composite Plates Subjected to Hydromat Test Key, C. T.*, Lua, J., Hess, P., Lopez-Anido, R.		Modeling of Blasting Processes in View of Fuzzy Randomness Moeller, B.*, Hoffmann, A., Liebscher, M.	
3:54	Bayesian Treatment of Expert Opinion in Earthquake Assessments Huyse, L.*, Gonzalez, S., Stamatakos, J., Thacker, B.		Uncertainty Management for Store Separation Using Belief Function Calculus Cary, A.*, Wesley, L.	
4:18	Uncertainty Quantification for Constitutive Models of Epoxy Potting Foam Hasselman, T.*, Wathugala, G., Hinnerichs, T., O'Gorman, C., Urbina, A.		Finite Element Method for Problems with Interval Parameters Zhang, H., Muhanna, R.*	
4:42	Model Validation of Encapsulating Foam Model Urbina, A.*, Paez, T., Hinnerichs, T., O'Gorman, C., Hunter, P.			
5:06	Uncertainty Quantification for Dynamic Analysis of Bolted Joints Hasselman, T.*, Wathugala, G. W., Paez, T., Urbina, A.			

INVESTIGATION OF RELIABILITY METHOD FORMULATIONS IN DAKOTA/UQ

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Reliability methods for uncertainty quantification are probabilistic approaches that compute approximate response function distribution statistics based on specified uncertain variable probability distributions. These response statistics include response mean, response standard deviation, and cumulative or complementary cumulative distribution function (CDF/CCDF) response-probability level pairs.

The forward reliability analysis algorithm of computing CDF/CCDF probabilities for specified response levels is called the reliability index approach (RIA), and the inverse reliability analysis algorithm of computing response levels for specified CDF/CCDF probability levels is called the performance measure approach (PMA). There are a variety of algorithmic variations that can be explored within RIA/PMA reliability analysis. The Mean Value method (MV) is the simplest, least-expensive method in that it estimates all response statistics from a single linearization in the space of the original uncertain variables ("x-space") centered at the uncertain variable means. All other reliability methods perform an internal nonlinear optimization to compute a most probable point (MPP) and then integrate about the MPP to compute probabilities. Within the MPP search methods, one may select among several different linearization approaches for the limit state function that can be used to reduce computational expense. Options include: (1) a single x-space linearization centered at the uncertain variable means (the AMV method), (2) the AMV method but with the linearization in the transformed standard normal "u-space" (the u-space AMV method), (3) an initial x-space linearization at the uncertain variable means followed by iterative x-space relinearizations at each MPP estimate until the MPP converges (the AMV+ method), (4) the AMV+ method but with linearizations in u-space (the u-space AMV+ method), and (5) no linearizations. In addition, one may select among different integration approaches for computing probabilities at the MPP, which currently include first-order and second-order approaches. Combining the no-linearization option of the MPP search with first- and second-order integrations results in the traditional first- and second-order reliability methods (FORM and SORM).

In the full paper, relative performance of these algorithmic variations are presented for a number of computational experiments performed using the DAKOTA/UQ software. Novel aspects in this study include (1) application of various linearization approaches to PMA, (2) full CDF/CCDF mappings with accurate warm starting of MPP searches, and (3) comparison of sequential quadratic programming and nonlinear interior-point optimization algorithms for the MPP searches. In addition, preliminary results are provided for the use of these RIA/PMA formulations for uncertainty quantification within reliability-based design optimization (RBDO).

COMPUTATIONAL METHODS IN RELIABILITY ANALYSIS

ROBUST MOST PROBABLE POINT SEARCH ALGORITHM FOR DIFFICULT PERFORMANCE FUNCTIONS

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The cornerstone of efficient probabilistic analysis methods is the ability to locate the most probable point (MPP) with as few function evaluations as possible. However, locating the MPP may be difficult or impossible in some situations and no single optimization algorithm is guaranteed to converge due to factors such as nonlinear or discontinuous response functions, the existence of multiple MPP's, or problems containing random variables with bounded (e.g., uniform) distributions. The cause of the MPP search failure has been identified for a number of problems and alternate solutions strategies adopted[1]. A cyclic behavior of the MPP location during the search is observed in a majority of failed cases. The authors propose a method based on the autocorrelation function of the MPP location during the search to detect this cyclic behavior. The failure of the search can be detected in as little as two cycles of the search when this form of failure occurs. Once a potential search failure occurs, a more robust yet computational MPP search algorithm can be used. Approaches for improving the convergence of the second MPP search by using information from the failed search are also presented. This paper includes several example problems demonstrating the approach.

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MOMENT-BASED STOCHASTIC AND DIMENSION-REDUCTION METHODS FOR STRUCTURAL RELIABILITY ANALYSIS

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Two new computational methods, referred to as the *moment-based stochastic method* and *dimension-reduction method*, have been developed for predicting reliability of structural and mechanical systems subject to random loads, material properties, and geometry. The first method involves calculation of the probability density function of the response and then determining reliability from the response distribution. In calculating response probability distribution, a moment-based quadrature rule is proposed that is based on the weighted sum of an appropriate integrand evaluated at selected realizations of random input. The method does not require exact probability density function of random input as it utilizes only finite moments of input variables and yet predicts reliability accurately. Hence, it is very effective when the probability distribution of input is not known, but only their statistical moments are prescribed. The second method is based on direct evaluation of a multi-dimensional integral over a safe set, which represents a part of the domain where a mechanical system is deemed safe. In this second method, authors' dimension-reduction methods, previously developed for calculating statistical moments, have been applied to calculate mechanical reliability directly as a multi-dimensional integral. However, in contrast to the calculation of statistical moments, which involves a multi-dimensional integral over an entire domain, reliability requires calculation of a multi-dimensional integral over an arbitrary domain. The calculation of the latter integral is more challenging than the former. Nevertheless, an innovative approach in conjunction with dimension-reduction methods has been developed to obtain reliability directly in addition to the moment-based stochastic method. Several numerical examples involving random fields and solid-mechanics problems illustrate the proposed methods. Results indicate that the proposed methods provide accurate and computationally efficient estimates of reliability.

COMPUTATIONAL METHODS IN RELIABILITY ANALYSIS

RELIABILITY ANALYSIS IN HIGH DIMENSIONS

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In the reliability analysis of a complex engineering structure a very large number of the system parameters can be considered to be random variables. The difficulty in computing the failure probability using the First and Second-Order Reliability Methods (FORM and SORM) increases rapidly with the number of variables or `dimension'. There are mainly two reasons behind this. The first is the increase in computational time with the increase in the number of random variables. In principal this problem can be handled with superior computational tools [1]. The second, which is perhaps more fundamental, is that there are some conceptual difficulties associated typically with high dimensions. This means that even one manages to carry out the necessary computations, the application of existing FORM and SORM may still lead to incorrect results in high dimensions. This issue has received little attention in the literature and this paper is aimed at addressing it. An *asymptotic approximation* for the case when the number of random variables $n \to \infty$ is provided.

The new asymptotic SORM is based on two types of approximations of the failure surface -(a) parabolic approximation in the transformed standard Gaussian space (as in conventional SORM), and (b) general quadratic approximation in the space of original non-Gaussian random variables. Simple closed-form asymptotic expressions are derived for these cases. The main outcome of the asymptotic analysis is that the conventional reliability index ß needs to be modified when $n \to \infty$. The proposed asymptotic approximations for $n \to \infty$ case are compared with existing approximations and Monte-Carlo simulations using numerical examples.

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LINKAGE GENETIC ALGORITHM FOR RELIABILITY ANALYSIS OF STRUCTURAL SYSTEMS

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The ability of Genetic Algorithms to identify local and global optima makes them especially suitable for solving structural reliability problems that essentially can be reduced to optimization problems in the standardized normal space. To reduce the known inefficiencies of traditional Genetic Algorithms, this paper proposes the use of a hybrid genetic search technique that is capable of efficiently identifying the dominant failure modes of a structural system and estimating their reliability index values.

The proposed algorithm combines the benefits and the efficiency of the linkage learning process of the Gene Expression Messy Genetic Algorithm (GEMGA) to the ability of the Shredding Genetic operator to explore new significant search domains. By reducing the dimensionality of the problem through linkage learning, the number of generations needed to reach convergence is greatly reduced. To further ameliorate the GA search's efficiency, the Shredding operator is used to estimate the value of the reliability index in a given search direction by building and updating a fitness value matrix based on an evolutionary learning process. This will drastically reduce the number of structural analyses that are required during the search. The implementation of an exploitation process during the search for the local optima will further help in obtaining accurate reliability indexes and quantifying the contributions of various variables to the structural failure modes identified during the search process. Examples will be provided to demonstrate the high efficiency and accuracy of the proposed hybrid Genetic Algorithm.

SIMULATION OF RANDOM HETEROGENEOUS MATERIALS

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The present paper deals with the problem of digital simulation of samples of random heterogenous materials. The latter consists of two or more distinct phases which are randomly distributed within the medium. Their random microstructure can be appropriately modeled using discrete valued random fields. In general, one is given a set of moments of marginal distributions that have been collected from actual samples, based on which the reconstruction procedure must be performed.

The simulation of samples of based on set of target probabilistic characteristics has attracted considerable attention over the years. The majority of the methods developed are based on nonlinear transformations (with or without memory) of Gaussian random fields ([1], [2]). Despite their advantages, they are able to match only the autocorrelation of the discrete random field, which implies a truncated description of the medium. A notably different approach was developed in ([3]) which is capable of incorporating higher order information using a time consuming stochastic optimization scheme that attempts to match the target characteristics with the ergodic averages over a single sample.

For practical purposes, one is interested in the values **I** of the random field that models the medium, at a discrete domain D which consists of a finite number of points, i.e. a $N \times N$ lattice. Generally, there exist more than one joint probability distribution functions $f(\mathbf{I})$ that have the target characteristics of the medium of interest. A common deficiency of the existing approaches is that, even though they prescribe intrinsically a distribution through the mapping or simulation algorithm used, no attention is paid on how this selection in made. Hence, no distinction is made between the distributions $f(\mathbf{I})$, essentially considering the *equivalent* for simulation purposes.

The present paper employs an alternative methodology in which the selection of the distribution is based on the Maximum Entropy principle that provides a naturally superior criterion for carrying out this task. The basic idea was first used by Zhu, Wu and Mumford ([4]) in the context of texture modeling based on a set of linear filters. Markov chain Monte Carlo procedures are used in order to calculate the parameters in the model and draw samples from the maximum entropy distribution. The present approach is able to incorporate an arbitrary amount of information and generate samples whose ensembles properties match the target. Examples for two-phase media will also be presented.

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ANALYSIS OF MATERIAL PROPERTY FIELDS FOR HETEROGENEOUS MATERIALS

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In modeling composite materials the assumption is often made that material behavior can be characterized by homogenized properties. For most engineering applications this is a good assumption. Damage phenomena, however, are often linked to local stress and strain concentrations which may be masked by homogenized properties. In many composite materials these phenomena may also not be deterministically defined due to the randomness of the microstructure. A more complete characterization of composite behavior should not only include details of the microstructure, to link the influence of microstructure to local material response, but should also offer a way to generalize predictions and model probabilistic response mechanisms through simulations.

In previous work, [1-4], a computational methodology was developed to characterize the spatial heterogeneity of a random composite using material property fields. The material property fields, based on material micrographs, form a discrete, spatially varying constitutive law. Advantages of the material property field description are that these fields can be easily input into finite element models and can be statistically characterized, facilitating material simulation studies. A disadvantage of the model is that no consistent criteria for model parameters, e.g., an appropriate window size, have been established.

The goal of the current work is to develop a means of experimentally validating the moving window methodology using Digital Image Correlation (DIC). “Large scale” composites were fabricated and mechanically loaded. Images of the undeformed and deformed material were analyzed using correlation based on the pattern of the microstructure. The measured strain fields from DIC are compared to those predicted by a FE model, which used the moving window material property fields as input. The proposed work will assist in further development and validation of the moving window micromechanics model.

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MECHANICS OF RANDOM MEDIA

NONLOCAL MODELING OF HETEROGENEOUS MULTISCALE SYSTEMS

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In the modeling of heterogeneous multiscale systems, subscale effects are usually taken account of by spatial averages of subscale variables over a moving window. However, the averaging process inevitably under-estimates the variability of variables since the fluctuation inside the window is smeared out. In our approach, random microstructural interactions are represented by nonlocal integration of subscale variables, which then becomes part of the constitutive equation of global state variables. The nonlocal integration term reflects the fluctuation of global states due to material heterogeneity. The kernel asso-ciated with the integration should be calibrated as a constitutive property. The global states, being the overall contributions accumulated from all the scales, must satisfy the admissible condition and boundary conditions. In this manner the behavior of a multiscale system can be stated as a boundary value problem. The nonlocal integration model of heterogeneous materials successfully predicts the boundary effects and size effects that otherwise cannot be explained by classical continuum mechanics.

The kernels for heterogeneous materials can be treated as nonstationary random fields, which are numerically represented by corresponding polynomial chaos expansions. The polynomial chaos coefficients are evaluated based on statistical samples of the Green’s function associated with a random distribution of microstructures. These samples are obtained by Monte Carlo simulation of the interaction between two representative microstructures. In combination with conventional finite element methods, the polynomial chaos expansion of the kernel can then be used to predict the behavior of a stochastic multiscale system.

A STOCHASTIC MICROMECHANICAL MODEL FOR THE BEHAVIOR OF HETEROGENEOUS MATERIALS

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The formulation of the general framework for a stochastic homogenization theory for elastic-inelastic heterogeneous media is presented. The theory is based on the use of probabilistic descriptions for the concentration tensors and, hence, for the localization effects in the different phases composing a heterogeneous media. First, the underlying assumptions and the associated implications are discussed. Next, results in the form of fundamental constraint equations and relations are presented. These results are independent of any particular form for the probability distribution functions of the localization effects. One method for obtaining particular forms for the probabilistic descriptors in the problem is outlined.

The general framework is specialized to the analysis of a two-phase composite system.
These results are subsequently applied to a number of different material types to illustrate the potential of the theory.

MECHANICS OF RANDOM MEDIA

TRANSLATION VECTORS WITH NON-IDENTICALLY DISTRIBUTED COMPONENTS: APPLICATION TO HETEROGENEOUS MATERIALS

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The translation model is a widely accepted method for generating realizations of non-Gaussian random processes and vectors. It has so far been restricted to stationary random processes, and random vectors with identically distributed components. Here the model is extended to allow the components of a translation vector to have non-identical marginal distributions. A derivation of the correlation distortion function is presented, along with indications that the approach may be further extended to model non-stationary, non-Gaussian random processes. The method is demonstrated by one purely illustrative example, and two taken from material modelling, namely the crystallographic orientation and the viscoelastic properties of polymer gels.

EARTHQUAKE ENGINEERING: SESSION 2

TIME-FREQUENCY LOCALIZATION IN STOCHASTIC SEISMIC MODELS VIA TIME-FREQUENCY ATOMS

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Some preliminary results on the use of time-frequency atoms for capturing the non-stationary frequency content of an ensemble of seismic records are presented. The results pertain to the temporal evolution of the effective mean instantaneous frequency of the seismic event, and the distribution of various parameters which describe the evolving spectral characteristics of the seismic event via the time-frequency atom formalism.

SEISMIC FRAGILITY ANALYSIS

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Seismic fragility is the probability that a geotechnical, structural, and/or non-structural system violates at least a limit state when subjected to a seismic event of specified intensity. Current methods for fragility analysis use peak ground acceleration (PGA), pseudo spectral acceleration (PSA), velocity (PSV), or displacement (PSD) to characterize seismic intensity. While these descriptions of seismic intensity are attractive for applications, they cannot capture the essential properties of the ground motion, since the probability law of a stochastic process cannot be specified by, for example its maximum over a time interval.

This paper uses an alternative characterization of seismic ground motion intensity based on the so-called seismic activity matrix, giving the relative frequency of the earthquakes with various moment magnitude m and source-to-site distance r. According to the specific barrier model the probability law of the ground motion process is completely characterized by m, r, underlying soil at the site and other parameters. The paper presents a method for calculating system fragility as a function of m and r, referred to as fragility surface. A structural/nonstructural system located in New York City is used to demonstrate the methodology. Fragility surfaces for different limit states are obtained for the system and its components.

FRAGILITY OF STEEL MOMENT FRAMES WITH NOVEL BEAM-TO-COLUMN CONNECTIONS UTILIZING SHAPE MEMORY ALLOYS

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In this paper, a comprehensive study of the seismic fragility of a steel moment resisting frame (SMRF) with fully restrained (FR), partially restrained (PR) and novel shape memory alloy (SMA) beam-to-column connections is presented.

The analytical performance evaluation studies are based on a 3-story model building designed according to UBC'94 and located in Los Angeles, CA. The PR model is adopted from the archival literature. A new fiber model for the innovative SMA connection is developed from moment-rotation relationships determined from full-scale experimental tests. This analytical model is implemented into a computational framework supported by the OpenSees finite element platform to evaluate the seismic behavior of buildings with the new connection. Non-linear time history analyses are conducted for a series of recorded and simulated ground motions that have been developed for Los Angeles to obtain the response of the building with the three different types of connections.

The variability in several structural frame response quantities such as the inter-story drift angle, total base shear, and maximum connection rotations is examined using an efficient Monte Carlo simulation technique. The statistical significance of the uncertainty in SMA connections, member flexure rigidies, and other uncertain factors is compared to the uncertainty in the ground motion through an analysis of variance. Finally, possible layouts for placement of SMA connections (perimeter frames vs. all frames) to ensure the optimal performance, along with the feasibility and fidelity of simpler methods (such as static push-over) to determine the most advantageous layout, are investigated.

ESTIMATION OF FRAGILITY CURVE BY USING LIMIT SEISMIC INTENSITY AND MARKOV CHAIN MONTE CARLO

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The necessity of effective method to estimate low failure probability is increased from the standpoint of evaluation of life cycle cost, risk and probabilistic safety assessment (PSA). In seismic PSA, seismic load and strength of a structure are often estimated separately. Probabilistic seismic load is modeled as a seismic hazard curve, whereas the strength with uncertainties is modeled as a fragility curve. We proposed estimation method of fragility curve by using Monte Carlo simulation and limit seismic intensity, which is defined as the minimum amplitude of input motion causing damage to a structure. When the seismic hazard is not so high, the tail part of the fragility curve is important to estimate failure probability accurately. For the effective estimation of the tail part, namely low conditional failure probability, we studied an effective Monte Carlo Simulation method combining with the progressive subspace concept which searches distributed failure event regions step by step [1]. Samples to search the failure region are generated in each subspace by using MCMC (Markov Chain Monte Carlo) [2]. Efficiency of MCMC is improved by simplifying the sampling procedure based on a uniform distribution from which it is very easy to transform into arbitrary distributions such as normal and log-normal distributions. Effectiveness of the proposed method is verified through numerical examples with simple limit state functions, then fragility curves of a bridge pier and a slope are calculated by the proposed method.

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A PROBABILISTIC EVALUATION OF THE SEISMIC RESPONSE OF A CITY

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Within the frame of the present paper, a probabilistic evaluation of the city-site effect is presented. The city-site effect is the modification of the seismic site response by the presence of a city. As a seismic wavefield impinges on the foundation of a building, the building vibrates and generates waves in the subsoil. In a city, different buildings interact due to the interference of the scattered waves.

In order to avoid a complete deterministic model of the city, a probabilistic city model is applied. The city is considered as a random set of resonant scatterers of which the only available information is the distribution of the resonance frequencies and the surface density of the buildings.

The equations that govern the city-soil interaction now become a set of stochastic equations. Based on these equations, the Dyson equation for the mean field and the Bethe-Salpeter equation for the field correlation are formulated. The approximating solutions of these equations allow to estimate the change of the mean site response through the presence of the city and the ratio of the coherent and incoherent site response.

The results are validated by means of numerical results obtained by means of a coupled FEM/BEM analysis for a deterministic model of a city quarter of Mexico City.

STRUCTURAL OPTIMIZATION USING INDUCTIVE IDENTIFICATION TREES

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Consider a structure with a high-dimensional vector of design parameters $x \in \Omega$ and performance function g(x).The search for the global optimum design, arg $\max_{x \in \Omega}$ g(x), is not possible except for the simplest structures because of dimensionality and the problems associated with multiple local maxima. In practical optimization, the focus is on generating a diverse set of design alternatives, S*, which are widely scattered in Ω and correspond to relatively high performance values. Once S* is collected, step-wise optimal search methods using gradients or other localized information in Ω can be used to improve the designs.

In this paper, we use feature-based classifiers for generating design alternatives. The attributes of the features are important to the effectiveness of the classifier approach. Features should be concise, with dimension much smaller than that of the original design space Ω, and informative, by providing insight into system characteristics. Furthermore, they should be complete, nonredundant, simple to evaluate, and aggregative.

The essential idea is to map designs in Ω into a relatively low-dimensional feature space *D*. A classifier is subsequently derived to search for high-performing design alternatives within *D*. We do not use genetic-algorithm-driven learning classifier systems that were pioneered by Holland and Goldberg; instead we use classifiers defined by inductive identification trees (*e.g.*, ID3, CART, IND, C4.5). Such inductive trees are well suited for data mining and pattern recognition applications and are arguably the most widely used algorithms in artificial intelligence. To use the algorithms in structural optimization, however, requires some significant modifications. We summarize several modifications that we have developed to make these inductive trees more effective in generating design alternatives.

Specifically, we show how feature-based classifiers defined by inductive identification trees can be formulated to: (1) provide multiple interfaces with domain experts, (2) elicit and encapsulate knowledge for design optimization, and (3) enable the transfer of optimization information between related systems.

IDENTIFICATION OF CRITICAL COMPONENTS AND CUTSETS USING LINEAR PROGRAMMING BOUNDS ON SYSTEM RELIABILITY

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The quality of life of people throughout the world depends on safe and reliable operation of civil infrastructure systems, such as highway transportation networks, ports and harbors, communication system, and water, gas and power supply systems. In order to improve the reliability of such systems against deterioration and natural and man-made hazards, it is important to identify their critical components and cutsets. Critical components are defined as components which make significant contributions to the system failure probability, relative to a specified system performance criterion and load hazard. A similar definition applies to critical cutsets. Recently, the authors developed a method for computing bounds on the failure probability of general systems (Song and Der Kiureghian, 2003a, 2003b). This method estimates the bounds in terms of marginal and joint component failure probabilities by use of linear programming (LP). The proposed LP formulation provides a convenient framework for a systematic identification of critical components. Once the bounds on the system failure probability are obtained by LP, simple calculations yield the ordered set of joint probabilities of system and each component failure events. This ordered set provides the order of importance of the components in terms of their contributions to the system failure probability. Numerical examples demonstrate the proposed method and the importance of identifying the critical components and cutsets.

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TIME-VARIANT RELIABILITY ANALYSIS USING A DIRECT SEARCH OPTIMIZATION METHOD

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Almost all numerical methods of time-variant reliability analysis require the determination of a design point, i. e. the most likely realization of the uncertain input variables within a failure domain defined by one or some combination of limit-state functions. This essentially represents a constrained optimization problem in standard normal space with a dimensionality of typically several hundred to thousand variables.

Fast and reliable gradient-based optimization methods have long been available. However, the computation of the derivatives requires considerable algorithmic effort, particularly if the failure domain is bounded by surfaces that are not differentiable, which is e. g. the case for nonlinear hysteretic systems. A possible procedure using a smoothing function for an example of the Bouc-Wen model is demonstrated in [1]. Unfortunately, even with a smoothing function a gradient-based optimization method can become unstable. It is therefore desireable to provide a stable algorithm that can be implemented in a straightforward manner for various systems with only minor modifications. The direct search optimization method “COBYLA” by M. J. D. Powell [2] is such an algorithm, because only function values of the objective and constraint functions need to be computed and a certain number of nonlinear inequality constraints can be easily taken into account. Powell, however, had originally tested his method only for a small number of variables.

This paper investigates the applicability and performance of the “COBYLA” method in the context of time-variant reliability analysis with a large number of variables and compares the results with numerical examples given in [1, 3]. While the quality of the obtained solutions is identical to those given in the literature and convergence is achieved in all cases, it turns out that the computational effort makes the proposed method impractical. This is because the linear interpolation used by the algorithm can be highly inefficient for a larger number of variables. In view of the exponentially increasing speed of computers, however, the method may still be an attractive alternative in the future.

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SEISMIC DESIGN OPTIMIZATION USING LCC-BASED RISK INDEX

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The author et al. developed a seismic risk management methodology of a building, where an alternative with the minimum LCC (Life-Cycle Cost) is chosen as an optimum selection [1, 2]. The LCC of each alternative was formulated based on renewal model for earthquake occurrences. In the formulation, we can directly utilize simulation models developed in relevant fields, e.g., seismology, geotechnical engineering, and structural engineering.

This paper proposes a new seismic risk index, which is defined as the ratio of the LCC to the required (codebased) design cost. The LCC includes, for example, costs for initial design, maintenance, repair/replacement after earthquakes and so on. Based on the simple index, an owner of a building can choose one optimum design that brings the minimum LCC among multiple alternatives.

As an example of the practical application, an actual office building in Tokyo is dealt with. The indexes of two design alternatives, one is a bare steel frame and the other is the same frame with oil dampers, are computed. In the computation of the LCC, two levels of simulation models, with and without time history analysis, are utilized. The results demonstrate that the installation of oil dampers is effective in reducing the LCC.

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DEVELOPMENT OF A MCT BASED VIRTUAL TESTING TOOL FOR PROGRESSIVE DAMAGE PREDICTIONS OF COMPOSITE PLATES SUBJECTED TO HYDROMAT TEST

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Uncertainty characterization for composite structural component behavior under load may be conducted either through extensive testing with large sample sizes, or by propagation of uncertainty through a predictive model whose input variable uncertainties are based on small scale, coupon testing. The prohibitive nature of extensive component testing has lead to the investigation of a test case of the latter approach. Statistically significant sample sizes of standard mechanical property tests are being developed and used to characterize the basic strength variable uncertainty of a glass fiber reinforced plastic (GRP) composite. This information will form the basis for numerical predictions of the uncertainty of a solid plate subject to lateral pressure. The predictions can then be compared to experimental test results so that the “virtual testing” approach may be validated. Fidelity of the numerical failure predictions is heavily reliant upon accurate modeling of progressive failure in the solid GRP panel.

This paper utilizes the constituent based progressive failure prediction tool coined multicontinuum technology (MCT), applied to composite plates subject to an out-of-plane, pressure load using “hydromat” testing. The hydromat test is a recently approved ASTM standard (D6416) that can reliably simulate in-use pressure loading conditions such as those experienced on the hull of a ship. The MCT failure prediction module has been numerically implemented and linked with the ABAQUS FEM solver via a user-defined material model. Multiple constituent-based failure criteria are used to predict failure associated with the fiber, matrix, and tow. The effects of plate thickness and lamination sequence on the initial failure and final rupture are explored and final conclusions are drawn about the validity of using the hydromat apparatus for testing solid laminates. Finally, the framework is presented for a multi-scale probabilistic analysis tool which is formed by integrating the MCT-progressive failure analyzer within a probabilistic analysis tool.

BAYESIAN TREATMENT OF EXPERT OPINION IN EARTHQUAKE ASSESSMENTS

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As part of the US Department of Energy's (DOE) evaluation of Yucca Mountain as a potential geologic repository for spent nuclear fuel and high-level, radioactive waste a probabilistic seismic hazard analysis (PSHA) has been performed. The report [Ref. 1] describes the process followed to carry out the PSHA Project and includes documentation of the interpretations and uncertainties used as input to hazard calculations from both the seismic source and fault displacement characterization and ground motion characterization.

Seven individuals, who are experts in evaluating the generation and attenuation of earthquake ground motions, have made ground motion assessments. The interpretations have been coordinated through a series of workshops. This process was designed to ensure that all credible interpretations are considered in the fault displacement and vibratory ground motion assessment. The seismic hazard computational procedures allowed quantitative assessments of seismic hazard based on the expert opinions. However, even upon completion of all the workshops, substantial differences remained in the uncertainty characterization assessments of individual experts.

In the original report, the uncertainty in individual assessments is captured as weighted alternatives and propagated through the hazard calculations. The hazard quantile curves as such incorporate both the inherent uncertainty due to random variability in the input parameters as well as epistemic uncertainty on the hazard due to lack of scientific knowledge and/or agreement between the experts. In this paper we compare these results with an alternative Bayesian approach [Ref. 2].

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MODEL VALIDATION AND UNCERTAINTY QUANTIFICATION: SESSION 3

UNCERTAINTY QUANTIFICATION FOR CONSTITUTIVE MODELS OF EPOXY POTTING FOAM

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Sandia National Laboratories is developing linear viscoelastic constitutive models for epoxy foams used to pot the electronics of weapon systems, and validating those models using experimental data. Part of the validation effort involves assessing the predictive accuracy of the models. ACTA has been working with Sandia to develop methods for quantifying uncertainty in the foam models based on experimental data. Within the hierarchical structure of the model validation process, validation begins at the unit level (e.g. with constitutive models of the foam itself) and progresses upward through the modeling hierarchy to component, subsystem and system levels which include the electronic packages, supporting structure, and other system components. Assessing the predictive accuracy of higher-level models based on lower level models and tests entails the propagation of uncertainty through the assembly of lower-level models into higher-level models. The conventional approach is to quantify modeling uncertainty in terms of the model parameters and propagate that parametric uncertainty by various means through the model to obtain an estimate of uncertainty in higher-level model predictions.
Unfortunately this approach does not account for all sources of the difference between model predictions and experimental measurements, even after accounting for experimental uncertainty. Nonparametric modeling uncertainty, e.g. due to inherent approximations in modeling assumptions, is one example. This paper will discuss alternative methods for uncertainty quantification and propagation that attempt to capture all sources of uncertainty contributing to the difference between analytical predictions and experimental observation. Practical examples based on uncertainty quantification at the constitutive material modeling level and propagated to the next higher level of assembly involving simulated electronics packages and structural components will be presented.

MODEL VALIDATION OF ENCAPSULATING FOAM MODEL

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Presently, there is an increased desire to use mathematical models to represent the behavior of complex physical systems. A complication in using mathematical models is the stochastic nature of excitations and the stochastic nature of structures themselves. Structures have been traditionally modeled using deterministic mathematical representations and the stochastic nature of the actual physical systems has been largely ignored. Our present study takes accounts of both the stochastic nature of physical systems and adds a probabilistic character to the mathematical models. Further, a formal procedure of model validation seeks to answer the question, in a probabilistic framework, "how good does a mathematical model represent a particular behavior of a physical system for a given application?" This work summarizes an approach to model validation that takes into account both the probabilistic and statistical nature of variation in mathematical models and the physical systems they are meant to model. A numerical example involving encapsulating foam is presented.

MODEL VALIDATION AND UNCERTAINTY QUANTIFICATION: SESSION 3

UNCERTAINTY QUANTIFICATION FOR DYNAMIC ANALYSIS OF BOLTED JOINTS

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Sandia National Laboratories is developing nonlinear dynamic models of bolted joints, and validating those models with experimental data. Part of the validation effort involves assessing the predictive accuracy of the models. ACTA has been working with Sandia to develop methods for quantifying uncertainty in the joint models based on experimental data. Within the hierarchical structure of the model validation process, validation begins at the unit level (e.g. with individual joints) and progresses upward through the modeling hierarchy to component, subsystem and system levels. Assessing the predictive accuracy of higher-level models based on lower level models and tests entails the propagation of uncertainty through the assembly of lower-level models into higher-level models. The conventional approach is to quantify modeling uncertainty in terms of the model parameters and propagate that parametric uncertainty by various means through the model to obtain an estimate of uncertainty in higher-level model predictions. Unfortunately this approach does not account for all sources of the difference between model predictions and experimental measurements, even when experimental uncertainty is accounted for. Nonparametric modeling uncertainty, e.g. due to inherent approximations in modeling assumptions, is one example. This paper will discuss alternative methods for uncertainty quantification and propagation that attempt to capture all sources of uncertainty contributing to the difference between analytical predictions and experimental observation. Practical examples based on uncertainty quantification at the single joint level and propagated to the next higher level of assembly involving several joints will be presented.

MODELING OF BLASTING PROCESSES IN VIEW OF FUZZY RANDOMNESS

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The controlled demolition of buildings that reached the end of their physical or economical life time is of increasing importance at the present time. On the one hand, there is a large number of buildings that are derelict or which no longer meet the present requirements. On the other hand, the resources of building land are limited, in particular, in densely populated areas. Based on this situation, the demolition of existing structures often represents an economical and sometimes the only way to allow new building. For removing reinforced concrete structures, demolition by blasting has become a common practice for technical and economical reasons.

The objective of blasting operations is to shatter a building in such a way that the remaining debris can be removed easily. When blasting operations are carried out in urban areas, the surrounding properties should not be affected by debris or accompanying ground vibrations. To obtain a dependable prediction of the collapse process and its effects, a realistic simulation is necessary. In the stochastic sense, each blasting is an individual event that is generally characterized by limited data and distinctive data uncertainty. The mathematical description of data uncertainty is realized on the basis of *fuzzy randomness* [1]. Fuzzy randomness is a generalized uncertainty model that includes fuzziness and randomness as special cases. In *fuzzy stochastic structural analysis* [1] the uncertain input parameters modeled by fuzzy randomness are mapped to fuzzy random results. The mapping is carried out by a so-called mapping model In the case of blasting a multi body system algorithm is applied as mapping model. The structure is divided in rigid and flexible parts. Flexible parts represent potential failure zones that are subject to the major damages or destructions during the collapse of the structure. This behavior is modeled by nonlinear load-deformation-dependencies that describe crack development, articulation, and failure.

The fuzzy stochastic analysis of blasting is demonstrated by way of an example.

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GENERALIZED MODELS OF UNCERTAINTY FOR ENGINEERING MECHANICS: SESSION 2

UNCERTAINTY MANAGEMENT FOR STORE SEPARATION USING BELIEF FUNCTION CALCULUS

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The safe release of stores from an aircraft provides a challenging and important engineering problem because of a sensitive dependence on a large number of parameters and the high cost associated with modeling or testing this class of problems. Additionally, in actual applications there are a large number of unknowns such as aircraft flight condition, store mass properties, and ejection force that can deviate from the nominal test conditions. Because of these effects and the potentially serious consequences of failure, uncertainty assessment is a necessary part of every store release. This paper discusses an approach using belief function calculus to model the uncertainty of a store separating from an aircraft based on estimates of uncertainty in input parameters.

Belief function calculus represents a generalization of Bayesian logic that leads to straightforward development of models that include uncertainty in the input properties and can easily be evaluated using computers to assess the likelihood of possible outcomes based on the available evidence and its credibility. Furthermore, uncertainty in the input can be explicitly indicated and this uncertainty is reflected as a range of confidences in the result. As additional evidence is gathered, the predictions can be easily enhanced to incorporate this additional data. The model can also be used in reverse to identify the pieces of evidence that are the most critical in a given case to assist in focusing areas for improving the quality of data.

A belief function model, characteristics of its implementation, and sample results for the store separation problem will be demonstrated to illustrate how heuristic beliefs, scientific relations, and data can be combined to provide a trajectory envelope and its associated confidence. In addition to providing estimates of uncertainty, this model provides a framework for discussing interaction of different effects that can be readily tested against available data and intuition to further refine the model. Several issues associated with the development of this model and its application will be discussed as lessons learned.

FINITE ELEMENT METHOD FOR PROBLEMS WITH INTERVAL PARAMETERS

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A new approach for the treatment of parameter uncertainty and rounding-off errors using interval arithmetic within the context of finite element method (FEM) is presented. Parameter uncertainties are introduced as interval numbers and outward rounding is applied to take care of rounding-off errors. Using interval mathematics, uncertainties and errors can naturally propagate throughout the system, leading to guaranteed reliable bounds on the “unknown” true system response. In recent years, two main categories of interval finite element method have been developed: optimization approach and interval approach. The interval approach is computationally efficient and provides guaranteed results, while the optimization approach is computationally expensive. The major difficulty associated with the interval approach is the overestimation problem due to dependency [1]: the computed range of the response is much wider than the actual range. Thus a naïve use of interval arithmetic in the formulation of interval finite element method, i.e., replacing real valued arithmetic by interval arithmetic, will result in meaningless wide results. In the present approach, an element-by-element technique is used to reduce the overestimation, and the compatibility conditions are ensured by the penalty method. In the case of linear static problems, the resulting linear interval system of equations is solved using the Brouwer’s fixed point theory with Krawczyk’s operator and a newly developed overestimation control. Most sources of overestimation are eliminated and a very sharp enclosure for the system response, due to loading and material uncertainty in linear static structural mechanics problems, is obtained. The resulting accuracy does not deteriorate with the increase of the number of the interval parameters or the size of the problems. A number of numerical examples are introduced. The present approach is also applicable to other uncertainty theories which rely on interval arithmetic for computations, such as fuzzy set theory, random set theory or probability bounds theory.

References

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Wednesday, July 28
8:30 – 9:30 AM

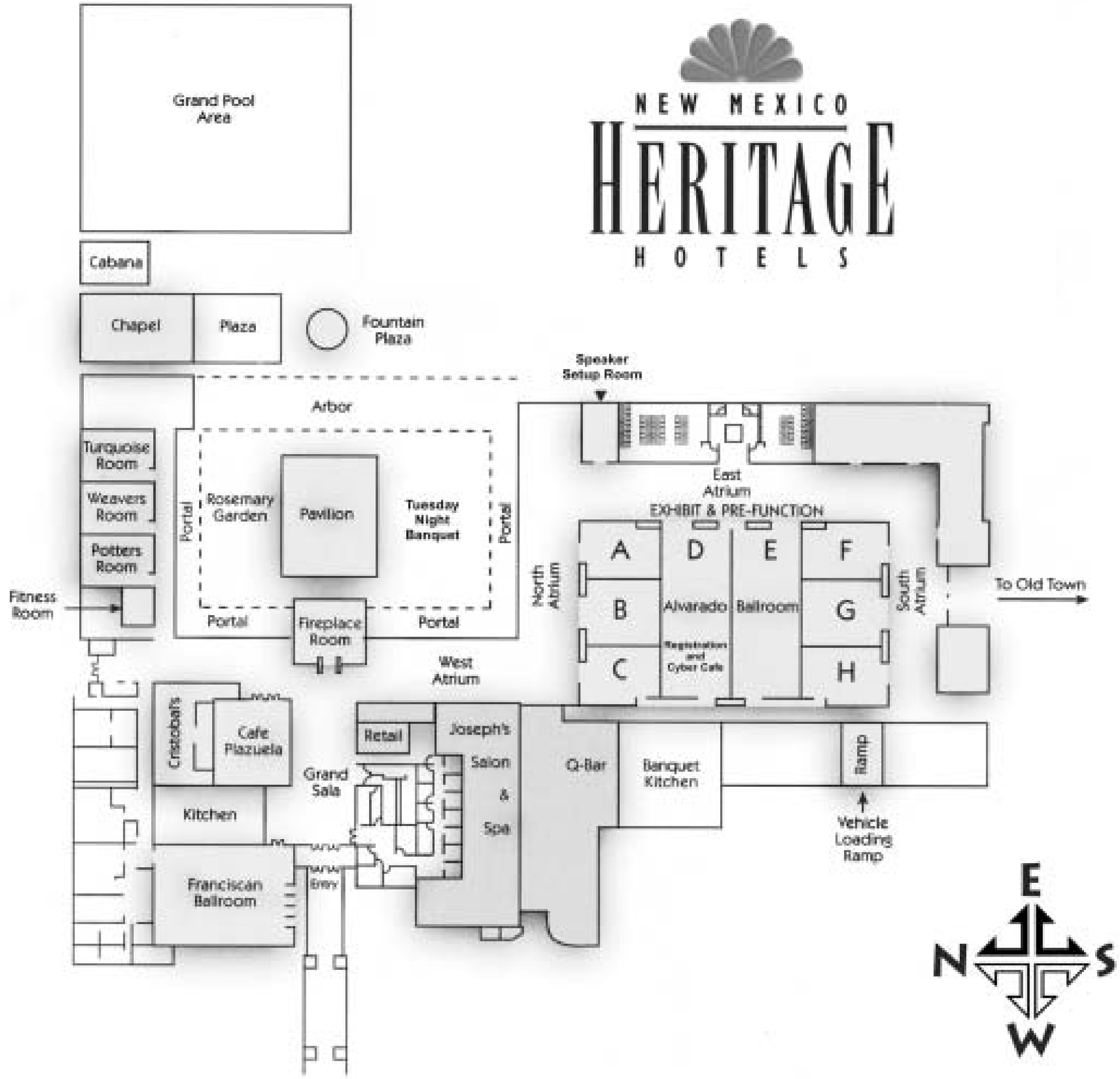
Plenary Lecture 3: Mircea Grigoriu

A Probability Path in Applied Science and Engineering

Major developments in probabilistic mechanics are related to relevant developments in probability theory and stochastic processes. While earlier results in structural reliability are based on classical concepts of probability theory, the formulation and solution of current random vibration, material science, and many other stochastic problems in applied science and engineering require advanced concepts of probability theory and stochastic processes.

Examples are presented to support these statements. The examples provide a critical review of some frequently used heuristic techniques in random vibration, rigorous methods for solving linear/nonlinear random vibration problems. It present specialized random fields needed to model polycrystals and two-phase material microstructures, use some of these microstructure representations and a local solution to calculate effective properties for random heterogeneous specimens, and outline some limitations of current stochastic finite element techniques. Applied to solve general stochastic problems. The examples also show that the use of advanced concepts of probability theory and stochastic processes can result in gross errors if developments involve heuristic assumption and/or mathematical technicalities are not considered carefully.

NEW MEXICO HERITAGE HOTELS



Wednesday Technical Program: 8:30 AM – 12:00 PM

Ballroom E	**Announcements and Plenary Session: 8:30 – 9:30 AM** A Probability Path in Applied Science and Engineering Mircea Grigoriu Cornell University
	WEDNESDAY MORNING, JULY 28: 10:00 AM – 12:00 AM
ROOM	**Technical Session Title**
Ballroom A	Sampling and Simulation Methods
Ballroom B	Uncertainty in the Characterization and Analysis of Jointed Structures
Ballroom C	Uncertainty Quantification of PDE’s
Ballroom F	
Ballroom G	Uncertainty Quanification Using Response Surfaces
Ballroom H	Bridge Maintenance, Safety and Reliability
Turquoise	

Technical Program: Wednesay, July 28: 10:00 AM – 12:00 AM				
Time 24 Min. Talks (* Speaker)	Room: Ballroom A **Sampling and Simulation Methods** Session Chairs: Deodatis, G., Naess, A.	Room: Ballroom B **Uncertainty in the Characterization and Analysis of Jointed Structures** Session Chair: Segalman, D., Slater, J.	Room: Ballroom C **Uncertainty Quantification of PDE's** Session Chairs: Soize, C., Red-Horse, J.	Room: Ballroom F
10:00	Optimal Representations of Stochastic Processes Red-Horse, J.*, Ghanem, R.	Investigation of Frictional Contact Parameters on Noise and Vibration in Mechanical System: Contact Damping Abdo, J.*	Analysis and Application of PDEs with Uncertainty: the Worst-Case Scenario Babuska, I., Nobile, F.*, Tempone, R.	
10:24	Evaluating Sampling Designs for Detection and Estimation in Spatial Fields McKenna, S.*	Failure Modes of Unstiffened and Stiffened Extended Shear Tab Steel Connections Mahamid, M.*, Rahman, A., Ghorbanpoor, A.	Time Dependent Partial Differential Equations with Uncertainty: the Stochastic Case Babuska, I., Nobile, F., Tempone, R.*	
10:48	The Use of Discrete Probability Distributions to Obtain Low Probability Event Estimates Kurth, R.*	Calibration and Variability of Hysteretic Models for a Single Bolted Lap-Joint Page, S., Shiryayev, O., Slater, J.*, Pettit, C.	Transient Transport Equations for Energy Propagation in Visco-Elastic Structures Impacted by Shocks Savin, E.*	
11:12	A Monte Carlo Approach to Sampling-Frequency Optimization and its Application to Pipeline Inspection Carrasco, C.*, Ferregut, C., Warke, R., Thacker, B.,	Probabilistic Modeling of Mechanical Joint Restoring Force Based on Experimental Measurements Hunter, N., Paez, T.*	Error Analysis of Composite Shock Interaction Problems Glimm, J., Lee, T., Li, X., Yu, Y.*, Ye, K., Zhao, M.	
11:36	Presentation of Twp Methods for Computing the Response Coefficients in Stochastic Finite Element Analysis Berveiller, M.*, Sudret, B., Lemaire, M.	Uncertainty in Parameterizing Experimental Joint Data Paez, T., Urbina, A.*, Segalman, D.	Non Gaussian Matrix-Valued Random Fields for Nonparametric Probabilistic Modeling of Elliptic Stochastic Partial Differential Operators Soize, C.*	

Technical Program: Wednesday, July 28: 10:00 AM – 12:00 AM				
Time 24 Min. Talks (* Speaker)	Room: Ballroom G **Uncertainty Quantification Using Response Surfaces** Session Chairs: Igusa, T., Agarwal, H.	Room: Ballroom H **Bridge Maintenance, Safety and Reliability** Session Chairs: Raphael, W., Faber, M.	Room: Turquoise	
10:00	Uncertainty Quantification Using Response Surface Approximations Giunta, A.*, Eldred, M., Castro, J.	Aspects of Sustainability in Engineering Decision Analysis Faber, M. H.*, Nishijima, K.		
10:24	Role of Computational Learning in Model Calibration Igusa, T.*	Reliability of Reinforced Concrete Bridge Decks Under Compressive Membrane Action Karimi, A.*, Ramachandran, K., Buenfeld, N.		
10:48	Response Surface Characterization Using Discrepancy Sensitivity Johnson, E. A.*, Wojtkiewicz, S. F.	Dynamic Progressive Failure of Bridges Banerjee, S.*, Shinozuka, M.		
11:12	A Design and Analysis of Experiments Approach for Parametric Studies of Penetration Events Marin, E.*, Chiesa, M., Booker, P.	Tacoma Narrows Bridge: A Case Study Issa, C.*, Kassaa, P.		
11:36	Evaluation of Nonuniform Centroidal Voronoi Tessellation for Statistical Sampling Romero, V.*, Burkhardt, J., Gunzburger, M., Peterson, J.	A New Approach for Creep Prediction of Prestressed Concrete Bridges Using Reliability Based Assessment Raphael, W.*, Mohamed, A., Mosalam, K., Calgaro, J.		

OPTIMAL REPRESENTATIONS OF STOCHASTIC PROCESSES

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In the context of computational stochastic mechanics, stochastic processes are typically represented by a denumerable set of random variables. This representation involves a linear transformation that, except for the Gaussian process, results in a new multi-dimensional measure attached to the variables. Optimal representations of stochastic processes refer to representations where the number of random variables required to achieve a given level of accuracy is minimal. It is well-known that the Karhunen-Loeve expansion provides a mean-square optimal representation for L^2 stochastic processes. This expansion involves solving an L^2 eigenvalue problem.

The present paper extends the Karhunen-Loeve expansion to functions in Sobolev spaces. These functions arise as solutions to partial differential equations in science and engineering. It is shown that the Karhunen-Loeve optimality can be extended to these functions by defining a new eigenvalue problem over the appropriate functional spaces.

SAMPLING AND SIMULATION METHODS

EVALUATING SAMPLING DESIGNS FOR DETECTION AND ESTIMATION IN SPATIAL FIELDS

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Design of sampling plans for spatial fields where the sample support is considered to be a point can be directed toward 1) the detection of discrete features of interest within the field (e.g., fatigue cracks in a component or “hot spots” in a environmental site characterization) or 2) accurate definition of the two-point spatial covariance function that can be used to estimate property values at unsampled locations across the sparsely sampled spatial field. Previous work has not simultaneously evaluated sample designs with respect to both goals. Eight different sampling designs are evaluated including square, triangular and hexagonal grids, random and stratified-random designs and two quasi-random sequences (Hammersly and Sobol). Numerical sampling experiments are evaluated with respect to the probability of detecting discrete features of different aspect ratios, bias and precision of the distributions of distances between pairs of samples as used in the calculation of a two-point spatial covariance function and the uniformity of the spatial coverage of the samples across the spatial domain. Results show that triangular grid sampling designs are superior for detection of discrete objects while stratified random designs perform best for producing even distributions of distances between sample points. The quasi-random sequences provide intermediate results with respect to both sampling goals.

THE USE OF DISCRETE PROBABILITY DISTRIBUTIONS TO OBTAIN LOW PROBABILITY EVENT ESTIMATES

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As infrastructures age there is a growing concern that deteriorating material, structural, and environmental conditions can lead to catastrophic failures. In the design condition the probability of such conditions existing are low enough that they may be safely ignored or controlled by the design. However, as conditions change and materials weaken these assumptions become less and less valid. Given the significant consequences low probability events, e.g. 1 in 10,000 or lower, can no longer be safely ignored.

Classically importance sampling methodologies have been employed in Monte Carlo simulations to assess low probability events. More recently adaptive methodologies for transformed density functions have been developed.1,2 Importance sampling methods for Monte Carlo become nearly intractable for complex engineering systems because it becomes increasingly difficult to remove the weighting function from the response sample. Adaptive methodologies provide fast, accurate answers for analytic functions. Unfortunately most engineering analysis does not employ analytic functions. In those cases, the standard practice is to employ response surfaces3 and analyze this approximation. The response surface will introduce a (usually) unquantifiable source of uncertainty unless one performs a Monte Carlo analysis to asses the uncertainty. In that case the adaptive methodology is useful if it is going to employed for various distribution types and parameters.

A third option is the use of discrete probability distributions (DPD's). In this analysis, the input distribution, if it is analytically described, is discretized into a finite number of values, each value having an associated probability. If the number of discrete values is denoted as NBIN and there are NV inputs to the analysis then to obtain the response DPD would require $(\mathrm{NBIN})^{N_V}$ calculations. For 100 discrete values and five input variables this would lead to 10,000,000,000 calculations. Clearly this would be no more efficient than the Monte Carlo analysis. However, if we treat the discrete space in the same manner as the continuous space we can employ a Monte Carlo sampling of the discrete space to obtain an estimate of the response DPD. In fact, the same statistical analysis procedures used for polling can be used.4 The distinct advantage that this method has over polling we know, *a priori*, what the value of each discrete point is as well as its probability! The advantage of this procedure in engineering analysis is that the input DPD can be discretized so that the probability of the input value occurring is not made to be equal at each discrete point. For example, the first value and last values of the DPD can be set equal to the 1 in 10,000 value. The placement of the points in between these limits is set according to an optimization algorithm. By placing the lumped probability mass at the interval conditional mean points the error in using the discrete point will be canceled out from the expectation calculations.

This paper demonstrates the advantages and disadvantages of these methodologies by examining two cases. The first is a theoretical example in which the response surface can be analytically calculated and comparisons of the DPD methodology to Monte Carlo and adaptive importance sampling analysis can be made. In this example it is demonstrated how events with probabilities of less than 1 in 1,000,000 can be estimated using 2,000 samples of the discrete space. In the second example the application of the methodology to a carbon-carbon structural component of a Mars satellite is made and compared to both Monte Carlo and adaptive importance sampling calculations. Boot strap techniques are used to estimate the uncertainty in the simulation methods.

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SAMPLING AND SIMULATION METHODS

A MONTE CARLO APPROACH TO SAMPLING-FREQUENCY OPTIMIZATION AND ITS APPLICATION TO PIPELINE INSPECTION

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Large and complex engineering systems require the implementation of maintenance protocols involving the inspection, assessment and maintenance or replacement of critical components to guarantee a desired level of service. The periodicity of the inspection schedule is set so that deteriorating components are identified, with a certain confidence level, before they fail.

Next, an assessment of the remaining capacity of the components to serve their intended purpose has to be conducted. To make this assessment process rational, it requires the availability of mathematical performance models of the components and means to compute the probability that the components will exceed their capacity. After computing the reliability of the components, a decision to keep, maintain or replace the component is made. This decision should be made by balancing the costs associated with replacing and maintaining the components and the expected economical and non-economical consequences of the failure of the system. Thus a cost optimized maintenance process has to be developed. Of course the larger and more complex a system is, the time and costs required to inspect all components becomes prohibitive. Strategies are needed to determine which and how many components (sampling frequency) need to be inspected if time and funds are limited. The more comprehensive the inspection process is, the more accurate the assessment of the reliability of the system is but the more expensive and time consuming.

This paper describes a Montecarlo based algorithm to determine the sampling frequency of relevant parameters that minimizes the inspection cost while maintaining a desired level of certainty in the estimation of the probability of failure of the system. The desired level of certainty is specified as an acceptable upper confidence limit and confidence level in the estimation of the probability of failure. The probability of failure is estimated using First Order Reliability Methods together with a pipeline girth-weld performance model. This algorithm is implemented in the GirthRel software tool initially developed to generate Reliability Based Assessment Diagrams for pipeline welds. The new "Sampling Frequency Optimization" module enhances the capabilities of GirthRel to include the development of a cost optimized girth-weld inspection protocol.

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PRESENTATION OF TWO METHODS FOR COMPUTING THE RESPONSE COEFFICIENTS IN STOCHASTIC FINITE ELEMENT ANALYSIS

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The Spectral Stochastic Finite Element Method (SSFEM) was introduced in the early 90's for solving stochastic boundary value problems in which the spatial variability of a material property (e.g. Young's modulus) was modeled as a random field [1].

The first part of this paper presents a new stochastic finite element procedure (SFEP) similar to SSFEM for problems that do not exhibit spatial variability. Precisely, the uncertainties in the material properties (for example Young's modulus and Poisson's ratio) and loading are described in terms of a set of any number of non necessarily Gaussian random variables. These variables are expanded in Hermite polynomial series.

An intrinsic representation of the system response onto the so-called polynomial chaos is used [1, 2]. The coefficients of the expansion are computed by a Galerkin-like procedure in the Hilbert space of random variables. The resulting linear system is solved either directly or using a hierarchical approach [3].

These coefficients may alternatively be computed by mean of a collocation method. As a result, a sequence of deterministic finite element problems is solved, which can be performed by any classical finite element code.

The second part of the paper compares the various methods of resolution in terms of accuracy and efficiency on an application example (convergence of a deep tunnel in an elastic soil mass). Precisely the values of the response coefficients, the associated statistical moments and the probability of failure associated with a prescribed failure criterion are compared.

References

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INVESTIGATION OF FRICTIONAL CONTACT PARAMETERS ON NOISE AND VIBRATION IN MECHANICAL SYSTEM: CONTACT DAMPING

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Friction-induced vibration continues to be a major challenge to designers in industry. This work is motivated by the realization that the phenomena of noise and vibration caused by frictional contact in mechanical systems must be related to the properties of the contact. Three parameters of interest, relevant to the vibration and noise response of a friction system, have been identified. These include the macroscopic effects of contact stiffness, damping and the friction function. Contact damping is considered in this study.

The development of the elastic-plastic contact formulae made it possible to investigate the contact damping by defining the equivalent damping coefficient due to plastic contact. As two surfaces are brought into contact elastic as well as plastic deformations occur. The elastic deformation, inherently, results in storage of energy. However, the plastic portion of contact results in energy loss from the system. The energy loss may then be incorporated into an equivalent viscous damping expression from which the equivalent damping coefficient is obtained. The results revealed the increase of the plastic energy loss with increase in the stroke length (compressive deformation amplitude), h_r. Similarly, the normalized equivalent damping coefficient, $c\omega$, increases with stroke length.

FAILURE MODES OF UNSTIFFENED AND STIFFENED EXTENDED SHEAR TAB STEEL CONNECTIONS

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The purpose of this research is to analyze and investigate extended steel shear tab connections using three-dimensional Finite Element Analysis (FEA). Standard shear tab connections require coping of the beam flanges and part of the beam web which cause lateral torsional buckling, local web buckling and block shear limit states, coping is also an expensive process. In an extended shear tab connections, the shear tab plate is welded to the web of the column, and it is connected to the web of the beam by tightened bolts. Extensive experimental work was done for this type of connections using variation of geometric parameters and configurations for beams, girders and columns in order to develop a standard design procedure for this type of connections.

The FEA presents a viable modeling procedure to effectively account for contact behavior and bolt tensioning technique. Contact is a strong nonlinearity and modeling techniques of contacts between surfaces taking into consideration the friction between the surfaces is a major task. Parameters such as friction and normal contact stiffness are very important parameters in establishing contact between the surfaces. Prior to applying the pre-tensioning force, contact surfaces should be created between the bolt and the surrounding structure. Contact surface is also created between the web of the beam and the shear tab. Successful modeling of this connection using FEA will result in tremendous time and cost savings as a validation of the results and as an alternative to the experimental investigation. In this research several 3D models with unstiffened and stiffened extended shear tab connections are modeled. The models are analyzed through the elastic and the plastic ranges up to failure. The finite element models are able to predict the behavior of the structure. Twist, Bolt shear, bolt bearing, and web mechanism are observed to be failure modes of the connections. Comparison between experimental and FEA results in the elastic and the plastic ranges shows that FEA has high level of accuracy with maximum deviation of 17% between experimental results and FE results.

UNCERTAINTY IN THE CHARACTERIZATION AND ANALYSIS OF JOINTED STRUCTURES

CALIBRATION AND VARIABILITY OF HYSTERETIC MODELS FOR A SINGLE BOLTED LAP-JOINT

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Uncertainty quantification (UQ) has been identified as an enabling technology for increasing reliance on analysis in airframe design and certification because it provides a formal path to model validation and prediction of performance variability. Practical applications of UQ to the dynamics of built-up structures require the ability to: (1) characterize the role of uncertainty in structural joints in governing their static and dynamic response properties, (2) propagate uncertain joint and other system properties through computational models of built-up structures to quantify response uncertainty, and (3) acquire experimental data to support validation of structural joint models that account for uncertainty.

A recent review paper [1] identified a definite need to characterize through carefully planned and conducted experiments the variability in the dynamic response of bolted joints and how this variability can be compactly represented in analytical models. The existing literature contains a variety of joint models, some of which are not suited to analyzing complex aerospace structures, or have not been developed or employed to accommodate the variability of joints that typically is observed in practice. As a result, experiments performed to identify model parameters typically suppress the observed variability in an effort to calibrate the deterministic behavior of the model. To support the eventual use of uncertainty-based computational models for airframe structural dynamics, the authors have developed an experiment for detailed dynamic measurements of bolted joint response and energy transmission. A primary goal of these experiments is to minimize variability associated with the measurement process so as to highlight the natural variability of the joint's mechanical properties, especially hysteresis induced by dry friction.

The full paper will cover initial results of performing these experiments for model calibration and validation. Particular attention will be paid to details of the experiment that have been designed to minimize the influence of imperfect boundary conditions on the measured response of the joint. Another focus will be characterization of nonlinear and time-dependent behavior of the joint (including dissipation and relaxation). Initial results from calibrating sample-to-sample variability in joint models will also be presented. Recently developed extensions of hysteretic joint models (e.g., [2, 3]) for micro- and macro-slip are being employed, so nonlinear system identification methods are an important component of this work.

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PROBABILISTIC MODELING OF MECHANICAL JOINT RESTORING FORCE BASED ON EXPERIMENTAL MEASUREMENTS

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The structural dynamic behavior of many mechanical systems depends critically on the local behavior of joints in the system. Mechanical joints affect both stiffness and energy dissipation. Further, it is widely known from experimental studies that mechanical joint behavior is random in the sense that repeated experiments with nominally identical joints yields randomly varying behaviors. Numerous mathematical frameworks exist for the simulation of the behavior of joints, and the parameters of these models can usually be identified directly from experimental data. When multiple data sets are available probabilistic models for their parameters can be developed. However, no attempt is usually made to simply use experimental data in a non-parametric framework to characterize mechanical joint behavior. The current investigation seeks to do this, and in addition to create a data-based probabilistic model. The idea of the response surface is used along with the Karhunen-Loeve expansion to develop a probabilistic model for mechanical joint restoring force as a function of relative displacement and velocity across the joint. An experimental/numerical example that develops the model for a particular mechanical joint is presented.

UNCERTAINTY IN THE CHARACTERIZATION AND ANALYSIS OF JOINTED STRUCTURES

UNCERTAINTY IN PARAMETERIZING EXPERIMENTAL JOINT DATA

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Almost every aspect of mechanical joints involves substantial uncertainty. Nominally identical joints might have noticeably different stiffness properties and dramatically different damping properties. Even the same joint after one assembly-disassembly cycle might behave visibly differently. Further compounding the problem, what constitutive models there are for mechanical joints are relatively new and not fully explored. Systematic methods to deduce model parameters from consistent and deterministic data are still under development – how one might deduce parameters with measured certainty nondeterministic and inconsistent is yet less clear.

The authors have begun addressing these problems by examining the sensitivity of a specific constitutive model to a realistic set of experimental joint data. This 4-parameter model was simplified to a 3-parameter model for the case where all data was taken well below the force of macro-slip. Though the nonlinearity of the model dictated that nonlinear couplings exist among the parameters, the original parameters were reformulated to make those couplings as understandable as possible. Forty-five data sets (representing five experiments each) were obtained from nine combinations of joint component assembled and disassembled five times each. The forty-five sets of model parameters were then processed to capture correlations and empirical dependencies. This information was then mapped back to the physical domain to define a nominal mean joint model and to establish levels of uncertainty to associate with that model.

ANALYSIS AND APPLICATION OF PDE'S WITH UNCERTAINTY: THE WORST-CASE SCENARIO

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Many physical problems are affected by relatively large uncertainty in the input data and the coefficients of the underlying mathematical model. In many cases, a full statistical characterization of those uncertainties is impossible to obtain and the only information available is a range where the input data and model coefficients can vary in. In this case, one can try to estimate the "worst-case scenarios" leading to the largest uncertainty interval in the output quantity of interest.

In this talk we present a technique, based on a perturbation method, to estimate the worst-case scenario, for elliptic PDE's with variable and possibly discontinuous coefficients. This technique is easily generalizable to account for uncertainty in boundary conditions and forcing term and is very computationally effective. We will give rigorous mathematical definitions, error estimation, convergence results and detail implementation aspects. Some numerical results will be presented as well.

Possible applications of this approach are: elasticity problems with variable and/or discontinuous material properties; flow in porous media with variable permeability; transport-diffusion phenomena with variable convection field.

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TIME DEPENDENT PARTIAL DIFFERENTIAL EQUATIONS WITH UNCERTAINTY: THE STOCHASTIC CASE

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We consider numerical approximations for the statistical moments of the solution of a time dependent linear partial differential equation (PDE) whose solution depends analytically on the coefficients of the PDE. When uncertainty is introduced and these coefficients are stochastic, we illustrate on the computation of the expected value and estimate the resulting numerical errors.

The stochastic coefficients of the PDE are approximated by truncated Karhunen-Loève expansions driven by a finite number of uncorrelated random variables. After approximating the stochastic coefficients the original stochastic PDE turns into a new deterministic parametric PDE of the same type. The dimension of the parameter set equals the number of random variables needed to approximate the stochastic coefficients in the original problem.

Since the solution of the parametric PDE problem is analytic with respect to the parameter variable we propose a tensor product approximation, the p-h version of the Stochastic Galerkin Finite Element Method (SGFEM),that uses a p version on the parameter set and an h version on the physical domain. This choice yields exponential convergence with respect to the order p. The results presented here generalize those given in [1,2] for linear elliptic PDEs with stochastic coefficients.

To compute efficiently the solution of the p-h SGFEM we use a special basis with double orthogonal polynomials. Thus, finding the solution entails solving a number of standard deterministic PDEs corresponding to different values of the parameter, precisely like in the Monte Carlo method.

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TRANSIENT TRANSPORT EQUATIONS FOR ENERGY PROPAGATION IN VISCO-ELASTIC STRUCTURES IMPACTED BY SHOCKS

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We apply some rigorous mathematical results obtained in the frame of microlocal analysis (Gérard *et al* 1997) to derive the exact propagation features of the high-frequency energy of randomly heterogeneous elastic structures excited by shocks. The theory shows that the energy observables satisfy transport equations, instead of the commonly assumed diffusion equations invoked by the structural-acoustics community. Such a diffusion limit can be obtained from transport phenomena only under certain circumstances which will be outlined in this communication. Our main focus is to extend the theory to the case of visco-elastic materials with memory effect: the transport equations remain basically unchanged in this case. We consider the example of a thick circular cylindrical shell to illustrate it.

Keywords
vibration, high-frequency, Wigner measure, transport, diffusion, random medium, visco-elasticity.

ERROR ANALYSIS OF COMPOSITE SHOCK INTERACTION PROBLEMS

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We studied repeated interactions of a spherically symmetric shock wave as shown in Figure 1. For each interaction, we performed numerical simulations on an ensemble of 200 initial conditions perturbed from a base case. The numerical solutions are obtained at mesh size 100, 500, and 2000. We use the difference between the fine-grid solutions (2000 mesh) and the coarse grid solutions as the numerical simulation errors. The created solution errors in wave strength, wave width and wave positions are modeled statistically with simple linear regression models in which the input conditions are the predictors. Then, we use a simple composite law developed in our previous works (Glimm et al, 2003) to combine the statistical models at each wave interaction to predict the errors after three shock wave interactions, both their means (bias) and their standard deviations. Our predictions are compared with the errors directly obtained through numerical simulation of the entire repeated shock wave interactions. Our prediction methods, although simple, works nearly perfect in all the cases except for the case of wave position errors of 100 mesh simulation. Note that the errors we obtained at the end come from two sources, numerical simulation and input uncertainty, propagated and transmitted through wave interactions. In this paper, we will conduct a detailed data analysis on the errors. One of our goals is to understand the relative importance between the imput uncertainty and the solution error. The other goal is to understand how each interaction contributes to the errors at the end of three wave interactions.

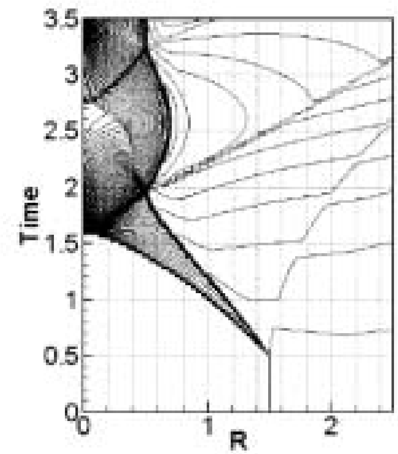

Figure 1: Space time density contour plot for the multiple wave interaction problem studied in this paper, in spherical geometry.

NON GAUSSIAN MATRIX-VALUED RANDOM FIELDS FOR NONPARAMETRIC PROBABILISTIC MODELING OF ELLIPTIC STOCHASTIC PARTIAL DIFFERENTIAL OPERATORS

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We present a new class of non Gaussian matrix-valued random fields whose system of marginal probability measures is constructed for that the matrix-valued stochastic partial differential operators on a bounded domain, constructed with such a random field, be an elliptic operator. It should be noted that no deterministic positive lower bounds are introduced to obtain an elliptic operator because the introduction of such a positive lower bound cannot be justified in many applications. The construction is then performed by using the maximum entropy principle and introduces a very small number of parameters in order to simplify the experimental identification. In a first part, we present the construction and study the properties of this class of matrix-valued random fields. In a second part, we prove that stochastic matrix partial differential operators on a bounded domain constructed with such a random field are elliptic random operators. Finally as an application, we introduce the nonparametric probabilistic modeling of the fourth-order tensor-valued field for a random anisotropic non homogeneous elastic medium. Such an approach allows a coherent construction of the 21 dependent random fields to be performed, in guaranteeing the mathematical properties of the random fourth-order tensor, while a direct parametric construction of the 21 dependent random fields would be unrealistic.

UNCERTAINTY QUANTIFICATION USING RESPONSE SURFACE APPROXIMATIONS

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An uncertainty quantification (UQ) study using traditional sampling-based approaches (e.g., Monte Carlo sampling and its variants) can be prohibitively expensive when applied to a high-fidelity simulation code that requires hours of supercomputer time for a single code execution. One approach to this dilemma is to perform UQ using a less expensive low-fidelity simulation code. However, this approach may not be acceptable if the low-fidelity code does not capture the salient physical phenomena of interest. An alternative approach is to employ response surface (RS) approximation methods to create a mathematical model of the high fidelity simulation code output data, and then perform UQ sampling on the computationally inexpensive mathematical model. In this RS-based UQ approach, statistical design of experiments techniques are used to select the input parameter settings for a few high-fidelity simulations, where the number of high-fidelity simulations is much smaller than the number of simulations needed for a traditional UQ study. Next, function approximation techniques, also known as response surface approximation techniques, are employed to construct computationally inexpensive mathematical models that map the variations in the simulation code output data with respect to variations in the design parameter values. Often these response surface approximations are low-order polynomials, but other models such as splines, kriging interpolation, and neural networks can be used as well. A UQ study is then performed via Monte Carlo sampling on the inexpensive response surface approximation model. This RS-based UQ approach yields the typical statistical metrics on the simulation code output data that are produced in a traditional sampling-based UQ study (e.g., mean value, variance, probability of failure). However, it is important to note that the RS-based UQ approach introduces additional error in the estimation of the statistical metrics beyond the error created by traditional sampling. Furthermore, the RS-based UQ approach is not well suited for certain applications, such as those involving very low probability of occurrence events. For these reasons, care must be taken in deciding whether or not to employ the RS-based UQ approach, as well as in choosing the design of experiments method and the mathematical form of the response surface approximation. The full paper will provide guidelines in these areas.

This RS-based UQ approach will be demonstrated on several test problems to illustrate both the utility and the shortcomings of this technique. In addition, this approach will be applied to an engineering design problem to demonstrate its suitability for use with computationally expensive high-fidelity simulation codes.

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ROLE OF COMPUTATIONAL LEARNING IN MODEL CALIBRATION

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For systems with significant measurement error and model discrepancy, low cardinality of data, and high dimensional uncertain parameter vectors, standard statistical methods are ill suited for the parameter calibration problem. Regression can lead to a response surface fitting process which does not systematically weigh the importance of the analytical models for the system, and Bayesian methods brings complexity to the probability models that overwhelms the underlying physics.

In this paper, an approach that is based primarily in computational learning theory is explored. Two key concepts are: (1) a function which quantifies model credibility over *domains* of parameters values and (2) the separation of uncertainty from variability. The motivation for using learning theory is to place the calibration problem in a wider, information-rich context. The goal is to derive a framework that can guide the process of model development, data collection, and expert knowledge incorporation in a systematic manner.

This research is in its early stages, and the results are primarily exploratory. One of the simplest computational learning approaches, based on classifier theory, is examined because of it is amenable to a Bayesian treatment of domain expertise. Generalized Kalman filters are also examined for their potential in extracting information out of residuals arising from incomplete models.

UNCERTAINTY QUANTIFICATION USING RESPONSE SURFACES

RESPONSE SURFACE CHARACTERIZATION USING DISCREPANCY SENSITIVITY

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Approximately uniform distributions of sample points are useful in certain problems in engineering and mathematics, notably optimization and uncertainty. Response surface methodologies benefit from an even distribution of sample points, not only over the input space but also over the output space, particularly in regions where steep gradients occur. The notion of uniformity can be quantified by the concept of discrepancy, which is a measure of the difference between a sample distribution and an ideal distribution — in this case, a uniform distribution. The authors have previously developed the concept of *discrepancy sensitivity*, a linear approximation for the change in discrepancy when adding or removing a particular sample point, as a numerical measure of a sample point's contribution to uniformity [1,2,3]. Essentially, discrepancy sensitivity quantifies the level of "new" information provided by a sample point, and should not be confused with conventional sensitivity analysis which looks at gradients of an input-output map.

This paper examines the efficacy of using discrepancy sensitivity on multi-input, multi-output problems. In particular, Branin's function [4], which is used as a testbed for studying optimization algorithms due to its multimodal nature, is used to investigate the methodology of using discrepancy sensitivity to choose new sample points so as to best characterize the surface based on the sample points. Several metrics of fidelity are used to quantify the accuracy. While the testbed functions used here are of trivial computational complexity, they exhibit some of the "difficult" behaviors — such as multimodality, sharp corners, and so forth that are typical of many real world applications. Some indications of the current work-in-progress and future directions are given.

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A DESIGN AND ANALYSIS OF EXPERIMENTS APPROACH FOR PARAMETRIC STUDIES OF PENETRATION EVENTS

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A numerical screening study of the interaction between a penetrator and a target with a preformed hole (created by a shape charge) was carried out to identify the main parameters affecting the penetration event. The planning of the numerical experiment was based on the orthogonal array OA(18,7,3,2), which allows 18 simulation runs with seven parameters at three levels each. The seven parameters chosen for this study were: offset, hole diameter, hole taper, vertical and horizontal velocity of the penetrator, angle of attack and target material. The analysis of the simulation results was based on main effects plots and analysis of variance (ANOVA), and it was performed using three metrics: depth of penetration, penetrator deceleration and maximum plastic strain on the penetrator case. This screening study has permitted us to rank the chosen parameters in order of importance and it is taken as a basis for uncertainty quantification studies of the penetration event.

UNCERTAINTY QUANTIFICATION USING RESPONSE SURFACES

EVALUATION OF NONUNIFORM CENTROIDAL VORONOI TESSELLATION FOR STATISTICAL SAMPLING

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A recently developed Centroidal Voronoi Tessellation (CVT [1], [2]) unstructured sampling method is investigated to assess its suitability for use in statistical sampling applications. CVT efficiently generates a highly uniform distribution of sample points over arbitrarily shaped M-Dimensional parameter spaces. It has recently been shown ([3]) on several 2-D test problems to provide desirable point distributions for response surface generation. More recently, for statistical function integration and estimation of response statistics such as mean, variance, and exceedence probabilities associated with uniformly distributed uncorrelated random-variable inputs to a system, CVT has been shown ([4]) to generate preferential sample sets compared to Latin-Hypercube Sampling (LHS) and Simple Random Sampling (SRS) Monte Carlo methods, and Halton and Hammersley quasi-Monte-Carlo (QMC) sequence methods. In this paper, CVT's performance as a statistical sampling method is further compared for non-uniform input distributions –specifically, uncorrelated normal input distributions. CVT's statistical sampling efficiency is shown to be superior to that of LHS and SRS Monte Carlo methods and Halton and Hammersley QMC methods for resolving various statistics of response in a 2-D test problem.

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[2]M. Gunzburger also supported in part by the Computer Science Research Institute, Sandia National Laboratories, under contract 18407.

ASPECTS OF SUSTAINABILITY IN ENGINEERING DECISION ANALYSIS

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Over the last decade significant developments in the area of civil engineering have taken place in regard to establishing rational and cost efficient decision making. This concerns e.g. the cost optimal or risk based design, maintenance and decommissioning of structures as well as concepts of life cycle costing as decision support for the evaluation of the feasibility of engineering projects. Furthermore, concepts such as the LQI, have been developed which may be utilized to assess the monetary resources which optimally should be spent by society on activities aiming to increase safety of the individuals of society.

In principle the common theoretical basis for all these developments can be said to be the decision theory and the adoption of the maximum expected utility in accordance with von Neumann and Morgenstern as measure of optimality. So far it has largely been assumed that decision, which are optimal in this sense are also sustainable. However, it has been well recognized that when societal decisions are made these always involve some tradeoff between economical benefits and the preferences of the stakeholders otherwise affected by the decision. This could concern the safety of individuals or damages to the qualities of the environment. Due to the fact that monetary values are involved in the decision problem it is necessary to take into account the effect of their net present value – which again depends on at what time the money have to be spend. This in turn leads to decisions which tend to favor a postponement of investments and at the same time favor decisions leading to incomes on a short term – all depending on the value of the real rate of interest applied as basis for the capitalization of costs and income.

With the view-point that civil engineering decision making can be seen as playing a game against nature it is obvious that the fundamental rule set is dictated by nature. However, we (man) being the conscious player in the game need to establish a set of strategies for playing the game which are in consistence with our fundamental moral and philosophical settings. These strategies might be seen as an extension of the basic rule set for the game. First when the rules of the game are well defined we can attempt to optimize our outcome.

The present paper first proposes two basic principles of sustainable decision making. It is then discussed how these basic principles of sustainable decision making can be applied in a context of decision making where monetary tradeoffs are made and the stake holders are individuals of society and nature. Thereafter the decision theoretical framework previously applied for the purpose of life cycle optimal decision making is reviewed and reformulated such that it becomes possible to optimize decisions in accordance with the basic principles of sustainable decision making. Finally an illustrative example is given on the application of the developed decision framework for a problem concerning the maintenance planning of a structure subject to degradation.

RELIABILITY OF REINFORCED CONCRETE BRIDGE DECKS UNDER COMPRESSIVE MEMBRANE ACTION

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It is widely acknowledged that in some instances reinforced concrete bridge decks have considerable strength reserves as a result of applied compressive forces. This phenomenon is referred to as compressive membrane action. However the beneficial contribution of compressive membrane action is often ignored in assessment.

In this paper yield line theory is extended to include the contribution of compressive membrane action to the ultimate load capacity of a laterally restrained reinforced concrete slab. The slab is idealized as a series of rigid plastic strips running in two directions and plastic theory is used to analyze the behaviour of each strip. Good agreement is obtained between theoretically predicted failure loads and experimental failure loads reported in the literature for a large number of laterally restrained slabs.

The first-order reliability method (FORM) is used to determine the reliability of a straight solid bridge deck slab clamped at both ends. The analysis is undertaken for a range of lateral surround stiffness values S and varying degrees of reinforcement corrosion at mid-span. The results of the analysis show that even in the presence of a very flexible surround, considerable improvements in the reliability of the deck slab are attained.

DYNAMIC PROGRESSIVE FAILURE OF BRIDGES

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Dynamic response of bridges under earthquake ground motion is discussed within the scope of this research. The progressive dynamic failure of bridges is studied using a model five-span bridge with expansion joint. To investigate the variation of bridge response with input ground motion, the model bridge is analyzed under three ground motions with various exceedance probabilities. Nonlinear finite element analysis is carried out using a bilinear hysteretic model for the bridge superstructure and nonlinear characteristics of the expansion joint. Based on the analysis, it is evident that expansion joint plays an important role to the failure of the bridge. Thus to avoid complete collapse due consideration should be given to expansion joints at the design stage.

TACOMA NARROWS BRIDGE: A CASE STUDY

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The dramatic Tacoma narrows bridge disaster of 1940 is still very important today.
Notably, in many undergraduate texts the disaster is presented as an example of elementary Forced resonance of a mechanical oscillator, with the wind providing an external periodic frequency that matched the natural structural frequency. In general, whenever a system is acted on by a periodic series of impulses having a frequency equal or nearly equal to one of the natural frequency of the system, the system is set into oscillation with relatively large amplitude.

Knowledge of engineering's failures is just as important as knowledge of its successes. Unfortunately, the engineering profession tends to highlight its magnificent successes while trying to forget its catastrophic failures. A success illustrates what engineering can make possible, while a failure demonstrates its limits. It takes numerous successful structures to ensure the quality of a design or a construction method. One failure, however, can discredit an entire design or building technique. Because of this reality, the information that each failure has to offer should be carefully studied and applied to all future designs.

In this study a finite element was generated to simulate the natural disaster that occurred and a comparison the modeling and the actual filming of the disaster would be presented.

A NEW APPROACH FOR CREEP PREDICTION OF PRESTRESSED CONCRETE BRIDGES USING RELIABILITY BASED ASSESSMENT

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Creep and shrinkage strains of concrete can have prejudicial consequences in prestressed bridges built by phases. In this work, a large collection database has been established for creep testing in many research centers in Europe. Firstly, a comparison is performed between the experimental results and the design codes of practice: BPEL, CEB, EUROCODE 2 and ACI. For all these codes, the creep deformation is, more or less, underestimated. For long-term creep, the error reaches sometimes more than 300%. This result has been confirmed by reliability analysis that we have carried out to check the weakness of the usual design codes.

In order to understand the possible reasons for the code deficiency, a reliability-based assessment is carried out for a bridge. A coupling between finite element tool and reliability software is realized in order to deal with complex mechanical behavior. The influence of creep parameter uncertainties is then quantified. Moreover, an intensive investigation of the considered limit states as well as the most probable failure point allows us to understand the behavior of the bridge towards creep strains and prestressing losses. The interest of reliability considerations in the qualification of design codes is shown in this study; this latter leads the designer to take into account the creep model uncertainties in an appropriate way.

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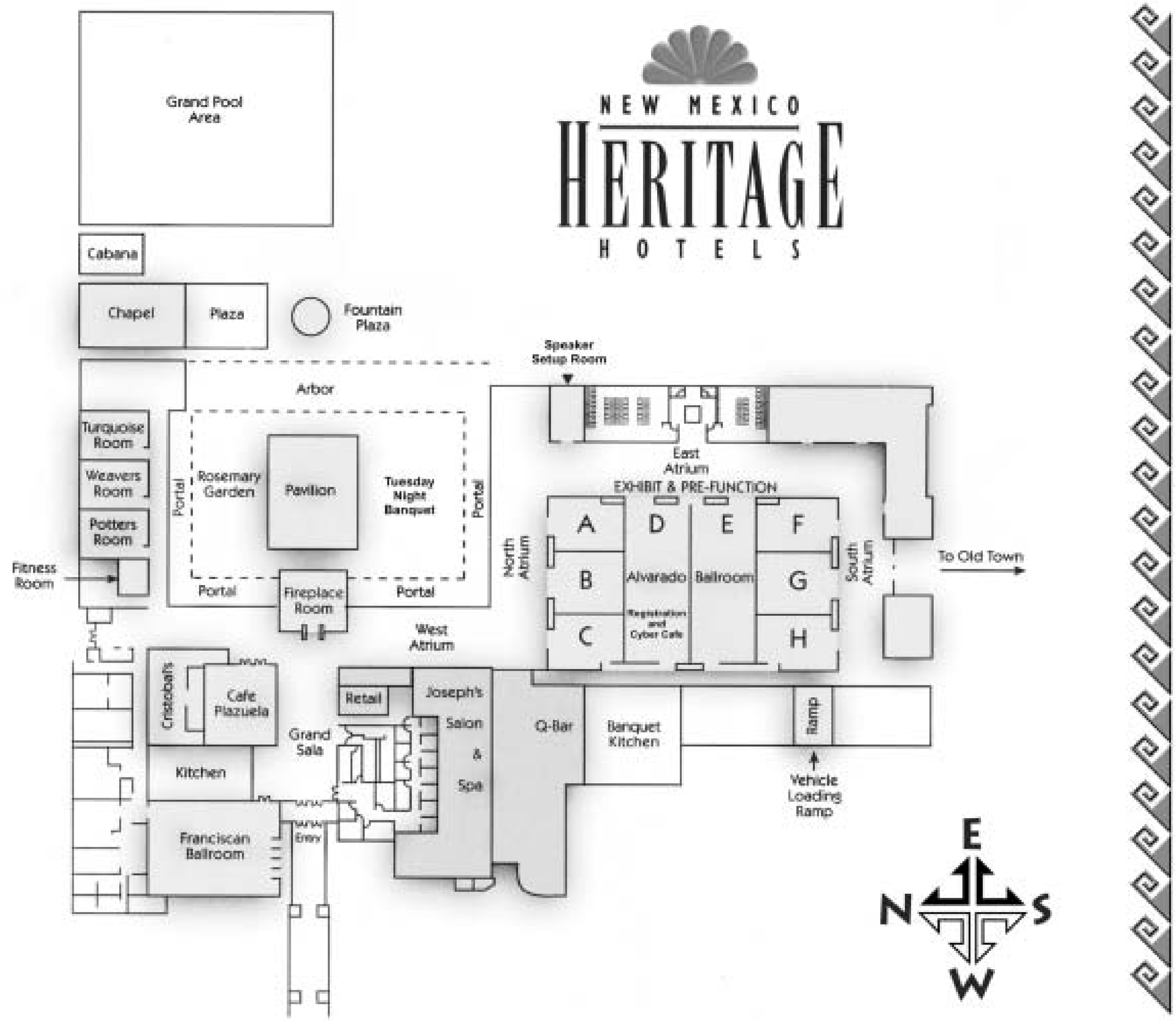
Map and Technical Program at a Glance


NEW MEXICO
HERITAGE
HOTELS
Grand Pool Area
Cabana
Chapel
Plaza
Fountain Plaza
Speaker Setup Room
Arbor
Turquoise Room
Weavers Room
Potters Room
Fitness Room
Portal
Rosemary Garden
Pavilion
Tuesday Night Banquet
Portal
Portal
Fireplace Room
Portal
East Atrium
EXHIBIT & PRE-FUNCTION
North Atrium
A
D
E
F
B
Alvarado Ballroom
G
C
Registration and Cyber Cafe
H
South Atrium
To Old Town
West Atrium
Cristobal's
Cafe Plazuela
Kitchen
Franciscan Ballroom
Grand Sala
Entry
Retail
Joseph's Salon & Spa
Q-Bar
Banquet Kitchen
Ramp
Vehicle Loading Ramp
E
N
S
W